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# INVESTIGATION OF THE LOW TEMPERATURE PERFORMANCE OF TRUCKS OPERATING ON LOW CETANE DIESEL FUEL - PHASE II

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DISCLAIMER

This study was carried out with the cooperation of the Department of Energy, Mines and Resources. However, the views expressed in the report are those of the author and do not necessarily reflect the views of the Department.

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## SUMMARY

An anticipated increase in diesel fuel demand and wider use of cracked and synthetic distillate fuel components prompted a study by Energy, Mines and Resources Canada, to assess the effect of such changes in fuel composition on truck cold weather startup and operability. A two-year contract was awarded to Esso Petroleum Canada, Research Department in 1985 to carry out a research program, using a Caterpillar 3406 heavy duty test engine for combustion tests and Class 8 trucks for cold starting and pull-away driving performance tests on the All Weather Chassis Dynamometer, AWCD.

Six fuels were blended to represent current and potential future quality Canadian diesel fuels, as defined by the Canadian General Standards Board. In general, the Caterpillar 3406 engine test phase showed that engine conditions have more influence than fuel quality on ignition delay and gaseous emissions. For example, increased cetane only slightly reduced nitrogen oxide emissions, and smoke, hydrocarbon and carbon monoxide emissions were unaffected. Ignition-improved and natural fuels of similar cetane and volatility provided equivalent cold starting performance and exhaust emissions. Reduced back-end volatility caused significantly more white smoke, but hydrocarbon and carbon monoxide emissions were only slightly raised. A synthetic fuel essentially gave equivalent performance to a conventional fuel, except for slightly lower nitrogen oxides emissions. Particulate emissions were not measured.

The AWCD truck testing established that engine design had by far the largest influence on startability and white smoke production. The engine variable that most influenced startability was coolant temperature, while compression ratio and fuel system design were of secondary importance. In contrast, fuel quality effects on startability were minor, except for the adverse effects of lower back-end volatility in the Caterpillar 3406 and synthetic fuel in the Cummins NTC-400. Compression ratio had a pronounced effect on white smoke production, but fuel quality effects also were important. Increased natural cetane and back-end volatility substantially lowered white smoke levels. Generally, chemically-enhanced cetane was not equivalent to natural cetane in control of white smoke, and a synthetic fuel produced no more smoke than its conventional counterpart. Engine design and ambient temperature had by far the largest influences on driveability. Few problems were noticed down to -25°C with the Caterpillar, Mack and Detroit Diesel trucks, but the Cummins' driveability degraded rapidly from -15°C to -25°C. Driveability was particularly poor with the higher viscosity fuels and the fuel/temperature sensitivity of the Cummins was suggested to be due to its relatively low compression ratio and/or its low vacuum fuel system. Fuel consumption generally increased with lower temperature and lower density, and varied substantially with engine model.

This final report concludes the low temperature diesel truck performance program, in accordance with EPCR's contract with the Department of Supply and Services, Canada.

## 1. INTRODUCTION

In the late 1970's and early 1980's the demand for diesel fuel was predicted to increase substantially, while inclusion of more cracked and synthetic distillate components in the fuel would put more stress on diesel "quality". The large rise in demand has not occurred, but there still would be significant economic benefits if the current CGSB cetane number specification of 40 was reduced to 37. These economic benefits would be realized via decreased operating costs, better fuel economy and improved crude oil utilization. Up until 1985, considerable work had been done on evaluating the performance of low cetane fuels at temperatures above 0°C, but not much accomplished at temperatures more typical of a Canadian winter. In 1983, a report on the investigation of trucks in the Canadian environment(1) proposed a test program involving a series of fuel/engine performance evaluations at several low temperatures. The proposal consisted of a series of multicylinder bench engine combustion tests, truck dynamometer starting tests on an AWCD and a small truck fleet trial.

For the eventual EMR-sponsored program, six test fuels were defined by the CGSB Diesel Fuel Panel, and were to be made from components processed from crudes and methods that Canadian refineries are expected to employ through the 1990's and beyond. Two key assumptions applied to this program were that the wider use of cracked and synthetic crude-derived distillate components might cause a significant deterioration in truck cold weather startup and operability, and that other possible adverse effects, such as increased emissions and shorter engine durability, might be tolerable. The program's overall objective was to investigate the effect of the anticipated change in the ignition quality and composition of possible future Canadian diesel fuels on the cold weather starting and pull-away driving performance of Class 7 and 8 trucks.

A two-year contract was awarded to Esso Petroleum Canada, Research Department in 1985 to blend sufficient quantities of the six fuels, carry out combustion tests on an instrumented Caterpillar 3406 engine stand over a 20°C to -25°C range, and carry out tractor tests in an all-weather chassis dynamometer over a 0°C to -25°C range. This document is the final report that presents and discusses the fuel blending, the Caterpillar 3406 engine test results, and the startup, cold idle white smoke, driveability and fuel consumption AWCD tractor test results.

## 2. TEST DESCRIPTION

### 2.1 Phase 1: Fuel Blends

The compositions of the six test fuels required to meet the specifications listed in Table 1 were established via small scale laboratory blending. Subsequently, about 1000 gallons of each of the test fuels were blended in EPC Research's tank farm at the Sarnia Process and Automotive Research Centre, SPARC. Final checks on critical properties were made and, when satisfactory, each blend was filter-coalesced and drummed.

### 2.2 Phase 2: Multicylinder Bench Engine Test

Phase 2 of this program involved bench engine testing, using a turbocharged-aftercooled Caterpillar 3406 engine whose specifications are summarized in Table 2. The six test fuels, blended in Phase 1, were evaluated in this engine under cold starting and steady-state warmed-up operating conditions. Details of the test program are summarized below.

2.2.1 Cold Engine Testing

(i) Starting temperatures of 20°C, 0°C, -15°C and -25°C.

(ii) Cold soaked engine at test temperatures for a minimum of 16 hours.

(iii) Three attempts of 30 seconds of continuous cranking at 2 minute intervals using warm batteries.

(iv) If engine did not start after the 3rd attempt, ether injection was used during the 4th attempt.

(v) Reported cranking time to start and cranking rpm.

(vi) Idled engine at about 840 rpm after starting and monitored white smoke continuously until the exhaust opacity was below 10%.

(vii) During idling, measured ignition delay at 3 minute intervals.

2.2.2 Hot Engine Testing

The following performance parameters were measured:

(i) Ignition Delay
(ii) Black Smoke Production
(iii) HC, CO, $CO_2$ and $NO_x$ Emissions
(iv) Rate of Cylinder Pressure Rise
(v) Peak Cylinder Pressure
(vi) Fuel Consumption
(vii) Exhaust Temperature

under the following operating conditions:

| RPM | Torque (N-m) | Averaged Intake-Air* Pressure (kPa) | Averaged Intake-Air* Temp. (°C) |
|---|---|---|---|
| 1200 | 775 | 31 | 80 |
| 1200 | Maximum Torque | 86 | 85 |
| 1600 | 475 (Equivalent to 50 kph Tractor Speed) | 31 | 81 |
| 1600 | Maximum Torque | 114 | 90 |
| 1800 | 630 | 53 | 83 |
| 1800 | Maximum Torque | 119 | 92 |

with the engine maintained at:

Coolant Temperature = 85-88°C

Oil Temperature = 91-95°C

Intake-Air Temperature = 80-92°C

* Note: Turbocharged Air after Aftercooler.

At each of the torque conditions, the engine was allowed to stabilize for about 5-10 minutes before the above performance parameters were recorded.

## 2.3 Phase 3: AWCD Truck Test

### 2.3.1 Test Vehicle Selection and Preparation

The four trucks chosen were fitted with engines representative of the most popular heavy duty diesel powerplants in Canada: Caterpillar, Cummins, Detroit Diesel and Mack. As indicated in the table below, the ratings ranged from 350 hp for the Mack E6-350 to 435 hp for the Detroit Diesel 8V92-TA. All four engines were turbocharged; the Detroit Diesel 8V92-TA is one of the most common engines of the only major 2-stroke heavy duty D engine builder in North America, and the other three engines were all 4-stroke DI designs. Displacements were 14.6, 14, 11 and 12.1ℓ for the Caterpillar, Cummins, Mack and Detroit Diesel engines, respectively.

| | Caterpillar 3406 | Cummins NTC-400 | Mack E6-350 | Detroit Diesel 8V92-TA |
|---|---|---|---|---|
| Rated Horsepower | 400 at 2100 rpm | 400 at 2100 rpm | 350 at 1800 rpm | 435 at 2100 rpm |
| Displacement, litres | 14.6 | 14.0 | 11.0 | 12.1 |
| Engine Cycle | 4-Stroke DI | 4-Stroke DI | 4-Stroke DI | 2-Stroke DI |
| Turbocharged | Yes | Yes | Yes | Yes |
| Compression Ratio | 14.5:1 | 14:1 | 15:1 | 17:1 |

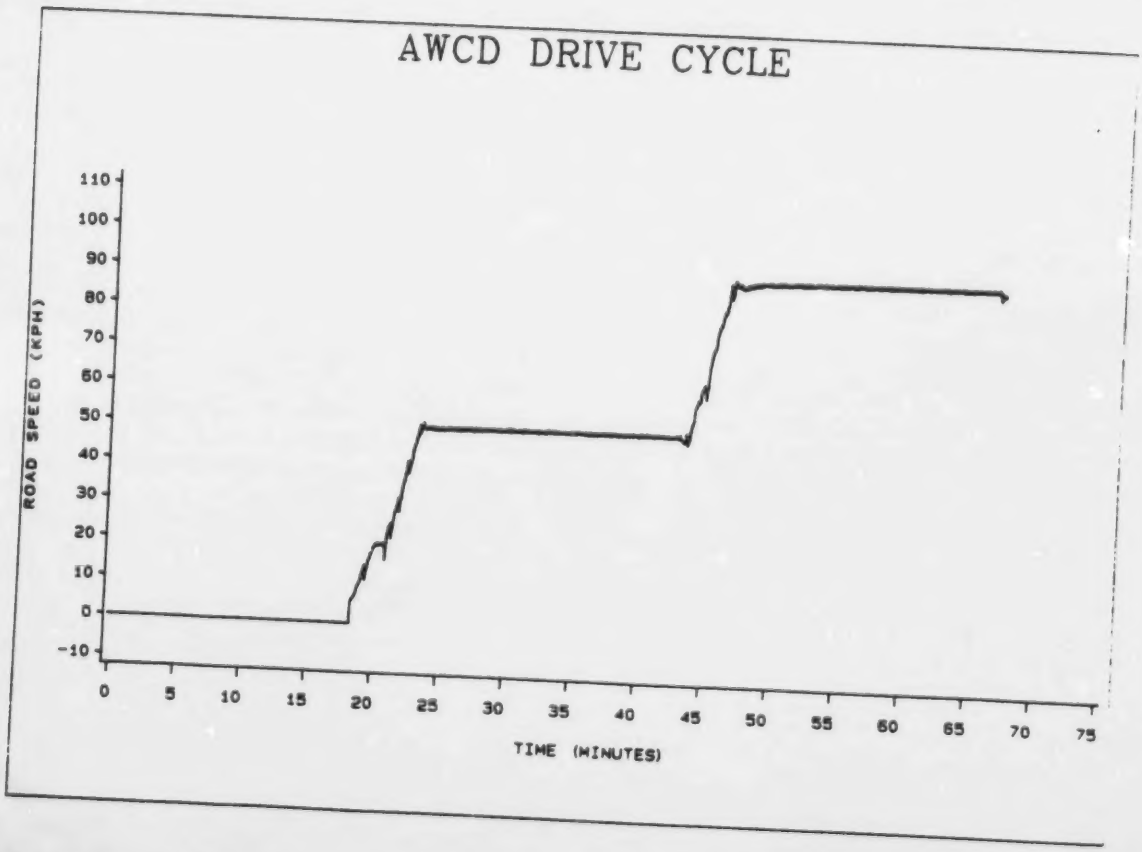
Table 3 lists more details of the four engines and chassis, such as the use of 2250 watts capacity circulating coolant heaters on the three 4-stroke engines, while the Detroit Diesel was fitted with a 2000 watt block heater. In addition, each engine was fitted with a 500 watt immersion oil pan heater and a remotely actuated ether injector kit. All four trucks were tandem axle cab-over-engine designs, and were built by four different chassis builders.

The four trucks were charged with lubricants that were considered adequate for ambient temperatures down to -30°C: Essolube XD-3 10W30 crankcase oil and Esso GX Extra Arctic 75W90 for both the transmission and differentials. The 10W30 crankcase oil was adequate since the oil pan heaters were always operational during overnight soaking. All four trucks were inspected thoroughly at a professional truck shop and were tuned to bring the engines up to manufacturers' specifications. Thermocouples were installed to permit continuous monitoring of various important temperatures, such as fuel, oil, coolant, air, exhaust, etc. The full list of parameters monitored is given in Table 4. Pressure transducers were installed before and after fuel filters, and an Airpax magnetic pickup was used to record rpm by counting the teeth on the ring gear portion of the flywheel. Exhaust white smoke opacity was recorded with an in-line Celesco 107 smokemeter. Times to first ignition and continuous operation were monitored by use of a voltage cable across the truck battery terminals, to measure increase of battery voltage on startup. Fuel consumption was monitored gravimetrically using a portable "diesel fuel cart" whose design is proprietary. The fuel cart's calibrated accuracy was ±0.4% on a mass basis, and repeatability much better.

Forty-five gallon drums were connected via Quick-Connects to the on-board fuel pump of each truck. The return line fuel also was re-routed to the drum. For each test run the drum was secured to the side of the truck and soaked along with the truck overnight. Use of such auxiliary drums for fuel supply permitted much faster fuel changes than would have been possible running from on-board saddle tanks.

### 2.3.2 Test Procedure

The daily test procedure is given in detail in Appendix 1. Briefly, at the end of each day the trucks were cooled to the desired test temperature by 8:00 p.m., followed by at least 12 hours overnight soaking at that temperature. Block or coolant heaters and oil pan heaters were employed in all tests, recognizing their routine use during Canadian winters. A successful cold start was followed by a minimum 15 minutes idling, and then linear acceleration to 50 kph speed and 62 hp road load. The speed was maintained constant for 20 minutes, followed by linear acceleration to 90 kph speed and 171 hp road load. 62 hp and 171 hp road loads represented actual highway operation of a 70,000 lb GVW truck at 50 kph and 90 kph, respectively. Following 20 minutes at a constant 90 kph, deceleration to 0 kph and 5 minutes of idling, the truck was shut down. The drive sequence was chosen to simulate actual practice over the road, and is illustrated in the diagram below. This type of drive sequence has been used successfully in other EPCR truck tests, both in the field and in the AWCD. The 50 kph speed segment may have been longer than common practice, but it was necessary to allow the appropriate fuel consumption measurements to be made. However, all of the driveability problems occurred during the acceleration to 50 kph or at that constant speed, so the relatively long 50 kph segment did not compromise the test results and conclusions.



The actual cold start procedure, shown schematically in Figure 1, included at least two attempts each of no more than 30 seconds duration. These first two attempts used the fully charged cold-soaked test truck battery, with a two minute interval between cranking periods to avoid starter motor overheating. Failure to start, or a stall, after a maximum of two attempts was followed similarly by two 30-second attempts with a so-called "hot" battery. This was a fully charged truck battery stored at 20-25°C and connected to the starter motor on the third and fourth starting attempts to provide greater cranking power. In those instances where the hot battery did not achieve a successful startup, ether injection and the hot battery were used in a fifth 30-second starting attempt. In any instances where a truck still failed to start or to sustain an idle mode, one final attempt was made using the hot battery, ether injection and short bursts of cranking, rather than 30 seconds of continuous cranking. Termination of this sixth starting attempt was entirely at the discretion of the professional driver, to avoid any harm to the engine.

During the subsequent idle and drive segments following successful startup, the appropriate data were recorded as discussed previously and listed in Table 3. In addition, the driver and observer in the truck cab recorded on log sheets subjective assessments of idle roughness, in-cab noise and driveability. Driver and observer log sheets are shown in Appendices 2 and 3, respectively. Fuel consumption was monitored continuously, but only the data recorded during the last 15 minutes of each constant speed segment were used to calculate an average fuel consumption value. The format of the daily fuel consumption report sheet is shown in Appendix 4. Following each day's first test run, the truck in the AWCD test cell was moved to the garage area and a second truck moved from the AWCD presoak area to the test cell. In this manner, three trucks were tested each day. Subsequently, the test cell and presoak areas were warmed to about -5°C, all three trucks were switched to the next day's test fuel and were idled for 10 minutes, to completely flush out the fuel system. Finally, the trucks were shut off and left to soak overnight at the desired temperature for the next test day.

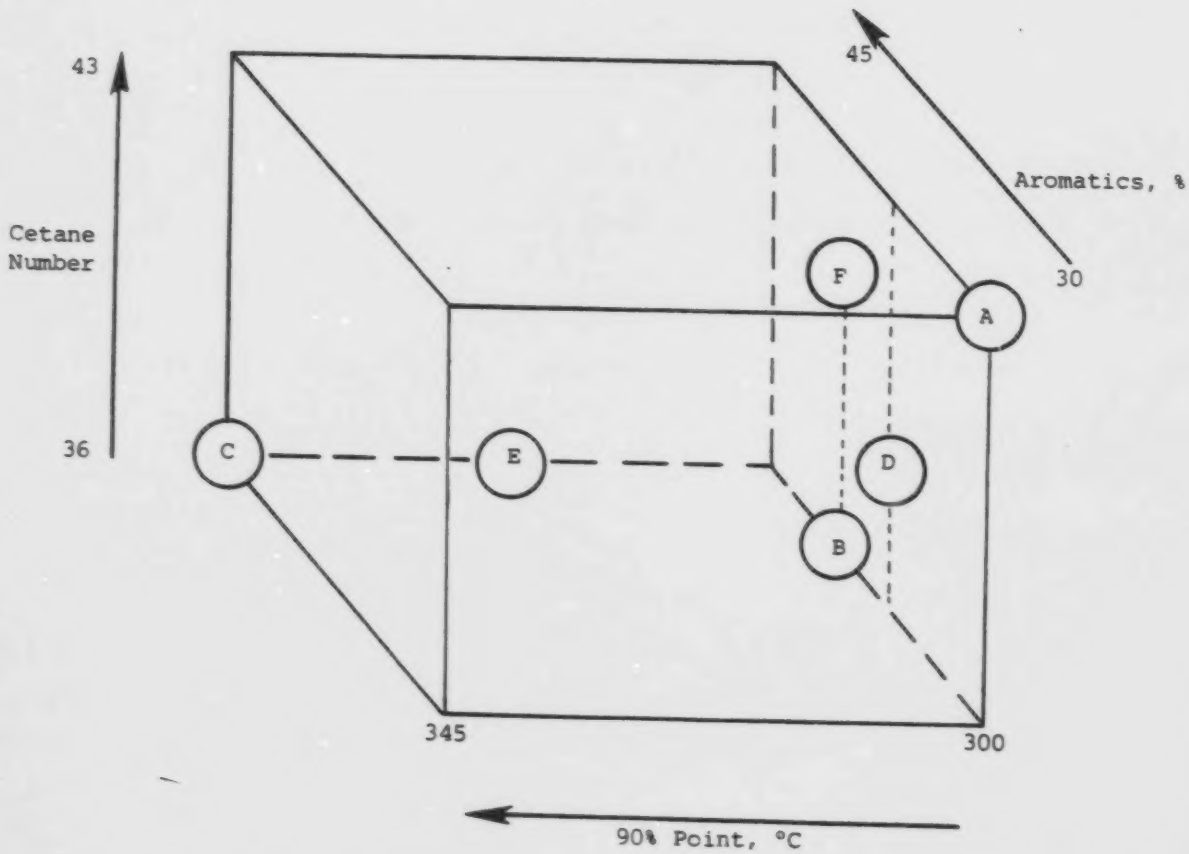
The requirements of the contract were that each of the six test fuels be tested at 0°C, -15°C and -25°C. Fortunately, the test schedule provided an opportunity to include a few extra tests at an even lower temperature. Three of the four trucks were tested at -30°C on Fuel E, and the results are discussed in the appropriate sections below.

## 3. RESULTS AND DISCUSSION

### 3.1 Phase 1: Fuel Blends

A matrix of six test fuels was chosen by the CGSB Diesel Panel to represent typical current and possibly commercially available future quality fuels. Briefly, the fuel quality characteristics of interest were cetane number, back-end volatility, ignition improver effectiveness and crude source. Component compositions are available in Appendix 5 and detailed inspections on all six fuels are listed in Table 5. Fuel A was a 42.5 average

natural cetane fuel, similar to many western Canadian fuels now and intended to represent the "minimum quality" fuel engine manufacturers would prefer for their engines. Fuel B was a 36.3 average natural cetane fuel with 306°C 90% point, intended to represent a high back-end volatility fuel with the lowest minimum natural cetane that might be available in the 1990's. Some current eastern Canadian winter domestic burner fuels are of this type. Fuel C was a 35.8 average natural cetane fuel with a 345°C 90% point, a low back-end volatility analogue of Fuel B. Some current eastern Canadian summer domestic burner fuels are of this type. Fuel D had a base cetane of 35.3 and was ignition-improved to 38.1 average cetane. The objective of Fuel D was for comparison with Fuel B, to examine the degree to which ignition improver can compensate for a lower base cetane and raise the quality to that of a comparable natural cetane fuel. Fuel E was a 35.6 average natural cetane fuel, composed mostly of components derived from hydroprocessing of synthetic crude. This fuel was chosen to study the effect of crude source; for example, by comparison with Fuel B, derived from conventional crude. Fuel F was an ignition-improved version of Fuel B, giving a 41.0 average cetane. The objective of this fuel was to quantify the boost in performance available by the use of ignition improver. The boundary diagram below summarizes pictorially the fuel matrix boundaries, with respect to cetane number, 90% distillation point and aromatics content.



Detailed specifications for all six fuels are listed in Table 1, as taken from the amended Statement of Work of February 7, 1986. All six fuels were within specification for the 40°C minimum Flash Point, 10% and 90% distillation point ranges, maximum sulphur limit, maximum Micro Carbon Residue, maximum water and sediment, copper corrosion, and composition requirements. The tight cetane number specifications for a 3 engine average value were considered unrealistic, given the repeatability and reproducibility of the ASTM D-613 engine test procedure. Nevertheless, considerable effort was expended in trying to meet this specification for each fuel. Fuels A, B and F met the cetane specification. At 35.8 average cetane, Fuel C just missed the target of 36 to 38, but both the CGSB Cetane Index and cetane calculated from $^1$H nmr data (Table 5)* confirmed that Fuels C and B were of comparable ignition quality. The need to achieve a minimum 90% point of 340°C resulted in a viscosity of 3.17 cSt for Fuel C, somewhat higher than the 2.0 to 2.2 cSt of four of the remaining fuels, but it was still within the test fuel specification. Fuel D's average cetane barely missed the specification's upper limit of 38, but again, the CGSB Cetane Index and cetane by $^1$H nmr data established significantly lower base fuel ignition quality than for Fuels B and C. Thus, comparison of Fuels B and D should provide a good measure of how well ignition improver equates with natural cetane.

Fuel E was intended to be completely derived from synthetic crude. However, as supplied from Shell's Scotford Refinery, the fuel had a cetane of about 33 and a 4.4 cSt viscosity. Accordingly, the fuel was blended with conventionally processed components to bring the cetane and viscosity within specification. The 35.6 average cetane was slightly low but the CGSB Cetane Index and cetane by $^1$H nmr data demonstrated similar ignition quality to that of Fuels B and C, rather than that of the Fuel D base. A brief summary table of the important fuel properties is shown below, to aid in following the text.

| Fuel | A | B | C | D | E | F |
|---|---|---|---|---|---|---|
| Cetane Number | 42.5 | 36.3 | 35.8 | 38.1 | 35.6 | 41.0 |
| Ignition Improver | - | - | - | ✓ | - | ✓ |
| 90% Point (°C) | 296 | 306 | 345 | 305 | 325 | 303 |
| Composition | Conv. | Conv. | Conv. | Conv. | Syncrude | B+ Ign. Imp. |

Thus, the objectives of the fuel matrix specifications were achieved and reported to the CGSB Diesel Panel in March, 1986.

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* Procedure used is detailed in "Cetane Number Estimation of Diesel Fuels from Carbon Type Structural Composition", B. Glavincevski, Omer L. Gulder and Leslie Gardner, NRC, SAE 841314, 1984.

## 3.2 Phase 2: Multicylinder Bench Engine Test

### 3.2.1 Cold Starting

The cranking times to start the Cat 3406 engine were measured at 20°C, 0°C, -15°C and -25°C, and the results are summarized in Table 6. At 20°C, all six fuels enabled startups immediately upon cranking. At 0°C, all six fuels provided startups quite readily during the first cranking attempt. Fuel A, with a natural cetane number of about 43, gave an easier start than Fuel B with a lower cetane number of about 36 (3 versus 12 seconds of cranking). Addition of 0.1 vol% of cetane improver to Fuel B, which then raised its cetane number to about 41 (Fuel F), improved the startability quite effectively. At -15°C, without the use of starting aids such as block heater or ether injection, only Fuel A enabled a start after 90 seconds (3rd attempt) of cranking. All the other fuels gave starts on the 4th attempt with ether injection. At -25°C, none of the fuels started the engine after the 4th attempt with ether injection but some of the fuels permitted start-up on the 5th and 6th attempts. The results suggested that increasing the cetane from 36 to 43 slightly improved startability.

Comparing Fuels B and C, it appeared that decreasing back-end volatility had no effect on startability. In addition, either natural compared to ignition-improved cetane or synthetic compared to conventional fuels showed no effect on startability.

### 3.2.2 White Smoke Production

The opacity of the exhaust was used as a measure of the white smoke level after start-up. Even at a starting temperature of 20°C, the initial white smoke levels for all six fuels were 100% opacity and this was primarily due to over-fuelling of the engine during cranking to start. During idling, the white smoke level decreased quite rapidly to less than 10% opacity in some cases. Therefore, the idling time required to decrease the white smoke level to 10% opacity was used as a measure of the white smoke propensity of the test fuels, and the results are summarized in Table 7. At a starting temperature of 20°C, Fuels A and B, with cetane numbers of 43 and 36, respectively, showed similar white smoke duration of 0.1-0.2 minutes. Increasing the 90% distillation temperature from 306°C to 345°C (Fuels B versus C) increased white smoke duration significantly from 0.2 to 2 minutes.

For all the test fuels, white smoke duration increased with decrease in the start-up temperature as shown in Table 7. Furthermore, fuel quality effects on white smoke duration became more apparent at low starting temperatures. For example, at -15°C, Fuel A (43 CN) produced less white smoke relative to Fuel B (36 CN). This demonstrated that higher cetane fuels produce less white smoke than lower cetane fuels. Addition of cetane improver was also quite effective in reducing white smoke (Fuel F versus B). Moreover, comparing Fuels B and D, it appeared that natural and ignition-improved fuels have similar white smoke levels. Fuel E, which contained substantial amounts of synthetic distillate components, produced slightly less white smoke than a conventional fuel (Fuel C) of similar cetane number. However, this slightly lower white smoke level could be due to a lower 90% point for Fuel E relative to Fuel C (325 versus 345°C).

### 3.2.3 Ignition Delay After Start-Up

After the engine was started from cold soaked periods at 20°C, 0°C and -15°C, the engine was idled at about 840 rpm, and the oil and coolant were allowed to warm up. In Table 8, the warm-up rate of the Cat 3406 engine after starting at -15°C is shown. The averaged oil and coolant temperatures at various idling times were used to illustrate the rate at which the Cat 3406 engine warmed up with the six test fuels. It can be seen that after 15 minutes of idling, the averaged oil and coolant temperatures increased by about 34-37°C. Directionally, there was a very slight increase in the warm-up rate with higher cetane fuels.

As the engine was warming up during idling, the ignition delay was monitored. In the present study, the No. 1 cylinder was instrumented to measure ignition delay. A strain gauge transducer was installed in the fuel line going into cylinder No. 1 to monitor its pressure and a piezo-electric transducer was installed in the No. 1 cylinder head to monitor cylinder pressure. Prior to fuel injection, pressure inside the fuel line will increase and then decrease as the fuel is injected into the cylinder. Therefore, the peak fuel line pressure was arbitrarily chosen to define start of fuel injection. The start of the rapid rise in the cylinder pressure was also arbitrarily chosen to define the onset of combustion, and the time interval between these two arbitrary yardsticks was defined as ignition delay, as shown in Figure 2.

The ignition delay after starting at 20°C, 0°C and -15°C is shown in Tables 9, 10 and 11, respectively. The data clearly showed the effect of oil and coolant temperatures on ignition delay. With gradual warming up of the engine during idling, ignition delay for all six fuels was found to decrease.

Immediately after starting at 20°C, Fuel A and Fuel B showed very different ignition delays of 3.4 and 4.58 milliseconds, respectively, due to a difference in their natural cetane numbers (43 versus 36). Interestingly, the corresponding cetane-improved Fuel F (Fuel B + 0.1% DII) showed essentially the same ignition delay as Fuel B, which suggested that cetane improver was not effective at idling conditions at 20°C. By comparing the ignition delays of Fuel B and Fuel F (Table 9), the effectiveness of the cetane improver in reducing ignition delay was seen to improve as the engine warmed up.

Directionally, this temperature effect on cetane improver effectiveness was also observed after starting at 0°C (Table 10), despite the fact that the measurement of ignition delay was not very repeatable due to erratic combustion at 0°C.

After starting the engine at -15°C, it can be seen in Table 11 that Fuels B, C, D and E misfired during the first 9 minutes of idling. Both Fuel A and F fired in cylinder No. 1 after about 3 and 6 minutes of idling, respectively, which is consistent with the fact that they have relatively higher cetane numbers than Fuels B, C, D and E. This probably explains why Fuel F produced less white smoke than Fuel B, because of reduced misfiring during the idling period.

### 3.2.4 Ignition Delay in a Fully Warmed-Up Engine

The ignition delay for the six test fuels was measured in the fully warmed-up Cat 3406 engine under six different rpm/torque conditions, and the results are shown in Table 12. Plots of ignition delay at 1200 rpm/775 N-m and 1600 rpm/475 N-m versus fuel cetane number are shown in Figure 3, and it can be seen that ignition delay decreased with increasing cetane number. In a fully warmed-up Cat 3406 engine, ignition-improved cetane was as effective as natural cetane in reducing ignition delay. Therefore, natural and ignition-improved fuels of the cetane number are expected to show essentially the same ignition delay. Decrease in the back-end volatility of the fuel (Fuel B versus C) did not affect ignition delay. Similarly, comparing Fuels C and E, the ignition delays under most of the test conditions (except at 1200 rpm and maximum torque) were very similar, and they showed that a mostly synthetic component fuel had similar ignition delay to a conventional fuel of the same cetane number.

For a given fuel at constant rpm, an increase in the torque decreased the ignition delay due to the following:

(i) Increase in the intake air pressure; for example, at torque levels of 775 N-m and 1495 N-m at 1200 rpm, the intake air pressures were 31.9 kPa and 83.9 kPa, respectively.

(ii) Increases in the intake air temperature from about 79°C to 85°C when the torque was increased from 775 N-m to 1495 N-m at 1200 rpm.

(iii) Higher rate of fuel injection at higher torque levels.

(iv) Higher torque also resulted in higher combustion temperature, thereby increasing the temperature of the residual combustion gas inside the cylinders.

However, because of the high compression ratio (low residual gas volume) and the turbocharging of the intake air, the effect of residual gas temperature on ignition delay probably was very small. This can be illustrated by comparing the effects on ignition delay at maximum torque for Fuel A as shown below.

| RPM | ID (ms) | Fuel Rate | Intake Air Pressure (kPa) | Intake Air Temperature (°C) | Residual Combustion Gas Temperature (°C) |
|---|---|---|---|---|---|
| 1200 | 0.89 | maximum | 83.8 | 85 | 595 |
| 1600 | 0.58 | maximum | 112.0 | 90 | 499 |
| 1800 | 0.44 | maximum | 113.9 | 92 | 465 |

At maximum torque at the three rpm levels, fuelling rate was at its maximum. However, at 1800 rpm, ignition delay was relatively the shortest because of the highest intake air pressure and temperature, despite the fact that the residual combustion gas temperature was relatively the lowest.

### 3.2.5 Cylinder Pressure

Diesel engine combustion can be separated into two stages, i.e. pre-mixed combustion and diffusion-controlled combustion. During the ignition delay period, fuel is continuously injected into the cylinder and mixed with air until ignition occurs. When ignition is subsequently initiated, the pre-mixed fuel-air mixture will burn very rapidly causing a rapid rise in the cylinder pressure, and this corresponds to the pre-mixed combustion stage. For fuels which have short ignition delay, fuel injection will continue beyond the start of ignition, and the combustion rate at this stage, which follows the pre-mixed stage, will be determined by the fuelling rate as well as the diffusion rate of fuel-air mixing. This second stage (diffusion-controlled stage) is usually characterized by a slower combustion rate relative to the pre-mixed stage. It is, therefore, reasonable to expect that a fuel with a longer ignition delay but similar fuelling rate would result in more pre-mixed combustion and hence a higher rate of cylinder pressure rise relative to another fuel with a shorter ignition delay.

The rates of cylinder pressure rise in kPa/CA° for the six fuels under the six different operating conditions are summarized in Table 13. The cylinder pressure rises at the intermediate torque levels are plotted versus the corresponding ignition delay in Figure 4. It can be seen that the rate of cylinder pressure rise was lowered with higher cetane fuels having shorter ignition delays. In other words, higher cetane fuels could result in lower noise.

Apparently, there is no correlation between the rate of cylinder pressure rise at maximum torque and the corresponding ignition delay because the fuel mass flow rate is substantially different between the six test fuels. For example, at 1800 rpm and maximum torque, the consumption rate of Fuels A and C were 746.5 and 814.4 g/min, respectively. Therefore, the average of the cylinder pressure rise at the three intermediate torque levels was used to assess the effects of the fuel properties on cylinder pressure rise as shown in Table 14. Decreases in the cetane number of the fuel increased cylinder pressure rise, which was probably a result of an increase in the ignition delay as discussed earlier. Similarly, addition of cetane improver to increase cetane reduced cylinder pressure rise. However, comparing Fuels D and B, the apparent reduction in cylinder pressure rise for the ignition-improved fuel relative to the natural fuel could, in fact, be due to higher cetane for Fuel D relative to Fuel B (about 38 versus 36). Decreasing the back-end volatility of the fuel slightly increased cylinder pressure rise. Comparing the conventional Fuel C with Fuel E, which contained large amounts of synthetic components, showed similar cylinder pressure rises if one could assume that the slight difference of 10 kPa/CA° was due to a back-end volatility effect.

The peak cylinder pressures obtained under the six operating conditions for all the test fuels are summarized in Table 15. For the same reason as discussed earlier, the peak cylinder pressures at intermediate torque levels were plotted versus the corresponding ignition delay in Figure 5. There was no correlation apparent between peak cylinder pressure and ignition delay. Higher combustion rate as a result of longer ignition

delay could result in higher peak cylinder pressure, but if the combustion extended well into the expansion stroke, the peak cylinder pressure would then be reduced. Thus, the lack of a simple correlation between peak cylinder pressure and ignition delay was not surprising, in light of the two opposing factors.

Interestingly, as shown in Figure 6, the peak cylinder pressures at maximum torque at the three rpm levels correlated with the fuel density. At the three maximum torque levels, ignition delay was probably short enough that most of the combustion had occurred near TDC (top dead centre) and, as a result, the peak cylinder pressure was more or less dependent on the total heat release from the fuels. This, in turn, was primarily a function of fuel density, because maximum fuelling rate was used per engine cycle. Therefore, it is not surprising to find that the maximum torque produced at maximum fuelling rate (summarized in Table 16) also correlated with the corresponding peak cylinder pressures as shown in Figure 7.

The results suggested that peak cylinder pressure was not dependent on the cetane number of the fuel (36-43). Since the peak cylinder pressure at maximum fuelling rate increased with increase in the heat content of the fuel, a lower cetane/higher density fuel could generate more power relative to a higher cetane/lower density fuel.

### 3.2.6 Black Smoke Production

The black smoke production data of the test fuels operating under the six test conditions are summarized in Table 17. The black smoke opacities at the intermediate torque levels are plotted versus ignition delay in Figure 8. In general, at these intermediate torque levels, all six test fuels produced very little black smoke (0.8-3.2% opacity), and there was no strong indication that black smoke production was affected by ignition delay.

For all six test fuels at constant rpm, increasing the torque increased black smoke production which was likely due to an increase in the fuelling rate. At maximum fuelling rate, i.e. maximum torque at 1200, 1600 and 1800 rpm, black smoke production was reduced slightly from about 4.5% to 3.5% opacity with increases in the rpm, which was probably due to increased intake air pressure and temperature.

It should be noted that even at maximum fuelling rate, i.e. maximum torque at the three rpm levels, all six test fuels produced very similar black smoke levels of less than 5% opacity. Thus, the black smoke production from a fully warmed-up Caterpillar 3406 turbocharged-aftercooled engine was quite insensitive to fuel property changes.

### 3.2.7 Hydrocarbon Emissions

The hydrocarbon emissions of the test fuels under the six test conditions are summarized in Table 18. In Figure 9, the hydrocarbon emissions of the six test fuels at three levels of engine power, 97 kW (1200 rpm; 775 N-m), 80 kW (1600 rpm; 475 N-m) and 119 kW (1800 rpm; 630 N-m) are plotted versus the corresponding ignition delay. Interestingly, it appeared that longer ignition delay reduced hydrocarbon emissions. However, the correlation of exhaust emissions with ignition delay for different fuels could be very deceiving because other fuel properties, such as volatility and aromatics, were also changed.

Another approach to examine the fuel effects on HC emissions was to compare the averaged HC emissions under the six different test conditions, as shown in Table 19. It can be seen that increases in the natural or ignition-improved cetane had no effect on HC emissions. Fuel E, containing significant amounts of synthetic components, produced essentially the same HC relative to a conventional fuel (C) of similar cetane number. Interestingly, decreasing the back-end volatility (increased $T_{90}$) slightly reduced HC emissions. In general, changes in the fuel properties had only very slight effects on HC emissions.

For all the test fuels at constant rpm, increasing the torque decreased hydrocarbon emissions which was likely due to increases in the intake-air pressure (Section 2.2.2), decreases in the ignition delay and thus increasing combustion duration and combustion temperature, as judged by the exhaust temperature, shown in Table 20. For example, at 1200 rpm, increasing the torque from 775 N-m to 1484-1580 N-m increased the exhaust temperature from about 450°C to 600°C.

The hydrocarbon emissions for all the test fuels at 1800 rpm and 630 N-m were relatively lower than those at 1200 rpm and 775 N-m, as shown in Figure 10, despite the fact that the exhaust temperature was lower at 1800 rpm than at 1200 rpm (385°C versus 450°C). Higher intake air pressure (53 versus 31 kPa, Section 2.2.2) and shorter ignition delay could be more important than combustion temperature in affecting hydrocarbon emissions.

### 3.2.8 Carbon Monoxide Emissions

The results for the carbon monoxide emissions are summarized in Table 21. The average CO production under the six different test conditions was used to assess the fuel effects on CO emissions, and the evaluation is summarized in Table 22. It can be seen that increases in either the natural or ignition-improved cetane had no effect on CO emissions. Decreasing the back-end volatility increased CO emissions. The apparent lower CO production from the synthetic distillate fuel (E) than from the conventional fuel (C) of similar cetane number could be due to higher back-end volatility of Fuel E.

For all six test fuels at a constant rpm, CO production at maximum torque levels was relatively higher than those at intermediate torque levels. At maximum torque levels (i.e. at maximum fuelling rate), the fuel-air ratios were probably much richer than at intermediate torque levels. The results suggested that the availability of air is probably more important than the combustion temperature in affecting CO emissions. Similar conclusions were reached by comparing the CO levels at maximum torque at 1200, 1600 and 1800 rpm for each fuel. At these three rpm levels and at maximum torque, the combustion temperature probably decreased with increases in the rpm (Table 22). However, for all the test fuels, a substantial decrease in CO production was observed when the engine rpm increased from 1200 to 1600. This was likely due to a substantial increase in the intake-air pressure from about 86 kPa to 114 kPa, although increased turbulence at higher rpm may have been another factor. Similarly, further reduction in CO with increase in rpm from 1600 to 1800 again was due to further increase in the intake-air pressure from about 114 kPa to 119 kPa.

It should be noted that the variation in the CO production between the six test fuels appeared to be less when the engine was operated leaner at 1800 rpm than at 1200 rpm. For example, at maximum torque at 1200 rpm and 1800 rpm, Fuels B and C showed a difference of about 110 ppm and 15 ppm CO, respectively. In other words, the effect of fuel property changes on CO emissions was relatively much less than the effect of engine operating conditions. Engine manufacturers could take advantage of this fact to design engines with reduced sensitivity to fuel property changes, thus lowering CO emissions.

### 3.2.9 Nitrogen Oxides Emissions

The results for the nitrogen oxides emissions are summarized in Table 23. Again, the averaged $NO_x$ production under the six different test conditions were used to assess the fuel effects on $NO_x$ emissions (Table 24). Increase in either the natural or ignition-improved cetane reduced $NO_x$ emissions. However, the effect of natural versus ignition-improved cetane on $NO_x$ emissions is not clearly understood. The "apparent" lower $NO_x$ production for the ignition-improved Fuel D versus the natural Fuel B in fact could have been due to higher cetane (38 versus 36). Decreasing back-end volatility did not have a significant effect on $NO_x$ emissions. Interestingly, Fuel E, which contained large amounts of synthetic components, produced less $NO_x$ than a conventional fuel of similar cetane.

In Figure 11, the nitrogen oxides emissions for all the test fuels under the same operating conditions were plotted against the corresponding exhaust temperatures. Assuming a correlation between combustion temperature and exhaust temperature, it appeared that $NO_x$ emissions increased with increasing combustion temperature. Furthermore, Figure 11 shows that combustion temperature had much greater effect on $NO_x$ emissions than did fuel property changes. In addition, the fuel effects on $NO_x$ emissions were greater at higher combustion temperatures.

### 3.2.10 Fuel Consumption

The fuel consumption, measured in g/min, for all the test fuels under the six operating conditions are summarized in Table 25 and reproducibility was generally within 1%. Since the test fuels had different density and calorific contents, it was therefore more meaningful to compare the thermal efficiency of the fuels based on their specific fuel consumption. The specific fuel consumptions (g/kW-hr) were then calculated and are summarized in Table 26. Again, the average of the specific fuel consumptions under the six test conditions was used to assess the fuel property effects on fuel economy (Table 27).

Decrease in the natural cetane increased the specific fuel consumption. Addition of cetane improver to increase cetane reduced the specific fuel consumption, presumably by increasing the thermal efficiency of the engine. There was essentially no difference in the specific fuel consumption between fuels of natural or ignition-improved cetane, and between conventional and synthetic fuels. Decrease in the back-end volatility also had no effect on specific fuel consumption.

However, consumers purchase on a volume basis, so it is more meaningful to measure fuel consumption also on a volume basis. Based on the density of the fuels, the fuel consumption in L/kW-hr are shown in Table 28. The averaged fuel consumptions in L/kW-hr under the six test conditions are shown in Table 29. Comparing Fuels, B, C and E which have very similar cetane number of about 36, the volumetric fuel consumption decreased with an increase in the density of the fuels. In other words, for fuels with the same cetane number, a higher density fuel would provide the consumer with better fuel economy, and this beneficial effect of higher density was not affected by either the inclusion of lower boiling or synthetic components. Comparing Fuels A and B, higher density and lower cetane number had opposing effects on the volumetric fuel consumption. In fact, Fuel B showed a very slight net fuel economy debit of 0.42% relative to Fuel A. However, it is likely that most consumers would not be able to perceive such a small debit, and lower cetane fuels (down to about 36 cetane) would be unlikely to cause a fuel economy drop.

## 3.3 Phase 3: AWCD Truck Test

The Esso Petroleum Canada Research All Weather Chassis Dynamometer is a world class facility capable of operating over a temperature range of -35°C to 40°C. One fixed and one moveable dynamometer allow the test cell to accommodate front, rear and four wheel drive vehicles, and tandem axle trucks. Thus, vehicles that can be accommodated range from sub-compact cars to Class 8 heavy duty trucks. Absorption power of 150 hp per dynamometer means that a total of 300 hp load at the wheels can be handled for tandem axle heavy duty trucks. Typical humidity range is 50% to 95% R.H. and maximum vehicle speed is 150 kph. In addition, the fan is computer-coupled to the

dynamometer speed so that wind velocity is synchronous with vehicle speed up to 110 kph. A pre-soak room adjoins the test cell, where five light duty vehicles or three heavy duty trucks can be temperature conditioned over the same -35°C to 40°C range, prior to moving into the test cell for dynamic testing. Alternatively, vehicles can be static tested in the pre-soak room; for example, startup and idle testing. Lastly, all of the above features are computer-controlled, together with data acquisition. Thus, the EPCR AWCD is an extremely flexible facility, that is primarily used for in-house product research and development of fuels, lubricants and other specialty products. However, these facilities are also used on a contract basis by companies in the automotive and petroleum products related industries, to complement their own product testing facilities.

The AWCD data accumulated by computer have been plotted against time for each of the test runs, and are available for reference in Appendices 7 to 81. As explained in Appendix 6, several parameters have been superimposed on each plot and there are five such "group plots" for each test run. By accessing the data tape to be provided, individual parameters can be viewed on a mainframe terminal screen, or single parameters can be superimposed for several test runs for ease of comparison. Each group plot in the Appendices includes both idle and drive segments of the operating cycle, but either segment can be studied in isolation by access of the data tape. Appendix 82 details the organization of the idle and drive files for each test run, to assist in using the tape data files.

The results, discussion and conclusions of the AWCD truck test have been assembled in several segments, relating to the specific truck performance criteria: cold starting, exhaust white smoke production, driveability and fuel consumption. Each of these performance characteristics was studied for the influence of fuel quality and composition, ambient temperature and engine hardware. All of these aspects are discussed in detail in the following sections.

### 3.3.1 Cold Starting

A brief summary of the most important cold start and white smoke data is given in Appendix 83, together with the appropriate computer runlist numbers. Individual test runs are discussed in detail in the various sections following. A general overview in Figure 12, of the cold starting performance of all of the trucks on all six fuels at -25°C, shows some significant effects. Total cranking time for all startup attempts was plotted against cetane number for the six fuels. The -25°C tests were chosen to illustrate the maximum performance differences observed. The most significant difference apparent from Figure 12 was the much longer cranking times for all fuels in the Detroit Diesel 8V92. The Caterpillar 3406 and Cummins NTC-400 showed long cranking times on Fuels C and E, respectively, but only small differences were noted for the five remaining fuels for each of the two trucks. For both trucks, successful startups with the five remaining fuels were within the first 30-second cranking period and the differences were not considered to be of much significance. The Mack E6-350 started within a few seconds on all six fuels at -25°C.

In summary, the Detroit Diesel proved very difficult to start at -25°C on all six fuels, requiring the use of the hot battery and ether injection. In contrast, the Mack also showed no fuel sensitivity but in this case, all starts at -25°C were achieved in under 5 seconds with the cold-soaked battery. Unlike the apparently fuel-insensitive Detroit Diesel and Mack, the Caterpillar and Cummins showed some varying response to the range of fuels, particularly at the lower cetane range of the fuel matrix.

3.3.1.1 Fuel Quality Effects

The sensitivity to natural cetane changes was evaluated for each truck by comparing Fuels A and B, as shown in Table 30. At -25°C, the lowest test temperature employed for all fuels except Fuel E, the Caterpillar, Cummins and Mack performed equally well on the 42.5 cetane Fuel A and on the 36.3 cetane Fuel B. For each of these three trucks, total cranking times were no greater than 8 seconds, and the biggest cranking time difference between the two fuels was 7 seconds in the Caterpillar. Even though the Detroit Diesel proved difficult to start on Fuels A and B, the difference was small. With Fuel A, cranking time was 95 seconds and the hot battery and one ether injection were necessary; with Fuel B, cranking time was 139 seconds and the hot battery and two ether injections were necessary. As apparent in Appendix 76, low cranking rpm (below 100) prompted abortion before the end of the 30-second cranking period for the first two attempts with Fuel A, but the general behaviour of this truck throughout the AWCD program did not indicate that an easier start would have occurred at a cranking rpm equal to that in the Fuel B test. The most notable difference between the two tests was that the 15-minute idle period was considerably more rough with Fuel B than with Fuel A. In summary, at -25°C, Fuels A and B provided essentially equivalent startup performance in the same trucks, but the Detroit Diesel was much harder to start than the other three trucks. A natural cetane reduction from 42.5 to 36.3 had no significant effect on ease of startup at -25°C.

A comparison of natural and ignition-improved cetane was accomplished using Fuels B and D. Fuel D had a base cetane of 35.3 and was raised to 38.1 average by addition of 500 ppm Ethyl DII-3 ignition improver. Although Fuel B had a 36.3 average cetane, the cetane calculated by $^1$H nmr (Table 5) indicated lower cetane for the Fuel D base than for Fuel B, and Fuel D contained a larger proportion of cracked stock. Thus, Fuel D base was of lower ignition quality than Fuel B and the Ethyl DII-3 raised Fuel D to a cetane level similar to that of Fuel B. Once again, the Caterpillar, Cummins and Mack started equally easily at -25°C on both fuels, with a longest total cranking time of 8 seconds. The results in Table 30 were 139 seconds cranking, hot battery and two ether injections for startup of the Detroit on Fuel B. On Fuel D, total cranking was 75 seconds, with the use of the hot battery and three ether injections. Unfortunately, the professional driver used ether on the third attempt instead of the fifth as indicated in Figure 1. However, he was of the opinion that the truck would not have started without use of ether and all the other -25°C tests of that truck support that viewpoint. The need for three ether injections with Fuel D was the only significant difference from the cold start with Fuel B.

Fuels A and F also provided a comparision of natural and ignition-improved cetane. 1000 ppm Ethyl DII-3 raised Fuel F from a base cetane of 36.3 to 41.0, comparable to Fuel A's natural cetane of 42.5. In this comparison, the ignition-improved fuel had much more cracked component than the natural cetane fuel, and the cetane boost was much larger; 4.7 for Fuel F and 2.8 for Fuel D. As before, the Cummins and Mack started up equally easily on both fuels, in 1 or 2 seconds. The Caterpillar took 1 second on Fuel A and 22 seconds on Fuel F, a slight relative deterioration but still a very easy startup. The Detroit required the hot battery and ether injections to accomplish startups on both fuels. Two injections of ether with Fuel F compared to one injection with Fuel A was the only difference noted, since the shorter cranking time with Fuel A mostly was the result of shortened cranking periods for the first few startup attempts due to low rpm. In summary, no significant startup performance differences were observed between the natural and ignition-improved fuels in each of two pairs, for the Caterpillar, Cummins and Mack. These results were not surprising, since the same three trucks showed no startability differences between Fuels A and B. An extra ether injection was required for the ignition-improved fuel in each pair, in the Detroit cold start tests. However, that small difference was identical to that between Fuels A and B in the Detroit.

One further aspect of ignition improver performance involves a comparison of a natural cetane fuel and the same fuel with ignition improver added, Fuels B and F, respectively. No significant difference in ease of startup at -25°C was detected between Fuels F and B, in the Caterpillar, Cummins or Mack. The largest difference was a 14 second increase for Fuel F in the Caterpillar, which probably reflected simply the repeatability of startup performance by that truck. For the three trucks, startups at -25°C on both fuels were very easy, accomplished on the first cranking attempt. In contrast and following an emerging pattern, the Detroit proved very difficult to start on either fuel. However, total cranking times were similar and two injections of ether were necessary on the fifth attempt in both cases. The only apparent difference was a smoother idle for Fuel F, which was reflected in a smoother rpm trace (Appendices 77 and 81 for Fuels B and F, respectively) and attested to the beneficial effect of the ignition improver. In summary, the ignition improver had no beneficial effect on already very easy startups for the Caterpillar, Cummins and Mack, nor on the very difficult startup of the Detroit. However, the additive appeared to promote smoother idling, following startup.

The impact of fuel back-end volatility was evaluated by comparing the performances of Fuels B and C, with essentially equal cetane but 90% points of 306°C and 345°C, respectively. The Cummins and Mack started equally well on both fuels in 15 seconds or less. Unlike its behaviour with the fuels discussed previously, the Caterpillar proved hard to start on Fuel C; total cranking time was 63 seconds and the hot battery was used, while it started up in 8 seconds on Fuel B. The rationale for this difference is that the heavier Fuel C would not evaporate as readily, nor form hydrocarbon vapour-air mixtures as readily in the combustion chamber, and thus would be more difficult to auto-ignite. The higher viscosity of Fuel C was a possible complicating

factor, but the high fuel line pressure system in the Caterpillar is unlikely to have been affected by the higher fuel viscosity. As observed in the previous comparisons, the Detroit proved very difficult to start on either fuel, requiring the hot battery and two injections of ether in both cases. No difference in ease of startup was detected for the two fuels, although heavy idle roughness was experienced for about 10 minutes on Fuel C but only about 3 minutes on Fuel B. Again, these observations are supported by the rpm traces in Appendices 77 and 78 for Fuels B and C, respectively. In summary, the Cummins and Mack started easily at -25°C on Fuels B and C, and were insensitive to the difference in the fuels' back-end volatility. The Detroit proved extremely difficult to start but startup response to each fuel was equivalent. The Caterpillar was the only truck that responded to back-end volatility, experiencing a difficult startup on the heavier Fuel C at -25°C.

The impact of the crude source was studied by comparing Fuels C and E, derived from conventional and synthetic crudes, respectively. Originally, Fuels B and E were intended for the comparison of crude source. However, the high viscosity of Fuel E prompted a substitution of C for B, since C has a similar viscosity to E. As reported in Table 30, again the Mack and Detroit showed no sensitivity; the Mack started up in 3 seconds on both fuels, while the Detroit needed the hot battery and two ether injections to achieve successful starts on each fuel. However, the Caterpillar and Cummins gave opposite responses to the two fuels. The difficult start on Fuel C for the Caterpillar reflected the low back-end volatility of that fuel. Fuel E, despite a high viscosity, had a more moderate back-end volatility (90% point of 325°C), resulting in a start after just 4 seconds of cranking. In contrast, the Cummins started after 15 seconds cranking on Fuel C, yet needed 105 seconds cranking and the hot battery to start successfully on Fuel E. As discussed above, the Cummins showed no sensitivity to back-end volatility, and so its poor startup on Fuel E probably was related to that fuel's composition.

The predominantly synthetic crude source of Fuel E would result in a much different distribution of hydrocarbon molecules than in Fuel C. An earlier paper(2) reported mass spectrometric compositional analyses of conventional and synthetic distillates:

| | Conventional (wt%) | Synthetic (wt%) |
|---|---|---|
| Paraffins | 39 | 17 |
| Naphthenes | 34 | 37 |
| Alkylbenzenes | 18 | 36 |
| 2-Ring Aromatics | 8 | 8 |
| 3-Ring Aromatics | 1 | 2 |

Using these data as a guideline, Fuel E would have a much higher proportion of alkylbenzenes than Fuel C, while Fuel C (which contained 25% cracked gas oil) would have a higher proportion of 2-ring aromatics. In addition, the paper reported nmr studies that concluded that the aromatic rings in the synthetic distillate were highly subsituted with methyl and ethyl groups, while the aromatic rings in the conventional distillate had fewer but longer alkyl side chains. Apparently, the ASTM D-613 cetane engine test procedure was not

sensitive to these compositional differences between Fuels C and E, but it is not surprising that at least one modern multicylinder heavy duty engine detected ignition quality differences at -25°C. In summary, the Caterpillar, Mack and Detroit showed no response to Fuel E's mostly synthetic crude source, in startups at -25°C. The harder startup on Fuel C for the Caterpillar was attributed to the high 90% point of that fuel. The Cummins was the only engine to show significantly harder starting with Fuel E.

The general conclusion drawn from the various comparisons in Table 30 was that the four test trucks showed surprisingly little sensitivity to substantial differences in fuel quality in cold starting tests at -25°C. No sensitivity was detected to cetane, ignition improver, or natural versus ignition-improved cetane. However, at some point, further reductions in cetane or temperature would be expected to adversely affect startability. The Caterpillar exhibited significantly harder starting on the low back-end volatility Fuel C, while only the Cummins startability was degraded on cold starting with Fuel E, the predominantly synthetic distillate fuel. The most significant effect obvious from Table 30 was the extreme difficulty in starting the Detroit at -25°C on any of the six fuels, while the Mack, Caterpillar and Cummins mostly started very easily. For this fuel matrix, the engine hardware variation was much more significant than the range in fuel quality. The effect of ambient temperature on startability is discussed in the following section.

### 3.3.1.2 Ambient Temperature Effects

It is interesting to study the joint effects of ambient temperature and fuel quality on startup, as shown in Figure 13 for the Caterpillar 3406. At 0°C and -15°C, the truck started in only 1 second on each of the six fuels. Even at -25°C, the total cranking times ranged only between 1 and 22 seconds for Fuels A, B, D, E and F. As discussed in the preceding section, only Fuel C resulted in a difficult startup for the Caterpillar at -25°C. Interestingly, the single -30°C Caterpillar test resulted in a still very easy 16 second startup on Fuel E. For the Caterpillar powerplant, it appeared that sensitivity to fuel back-end volatility was more pronounced than to ambient temperatures down to -30°C.

The analogous plot of total cranking time against test temperature for the Cummins NTC 400 in Figure 14 similarly showed no effect by temperature down to -15°C. Startups on all six fuels were achieved in 2 seconds maximum. Again, at -25°C five of the fuels permitted easy startups, the cranking times ranging from 1 to 15 seconds. Only Fuel E caused hard starting problems, necessitating the use of the hot battery. At -30°C, the same fuel required the use of the hot battery and ether injection to achieve startup. No other fuels were tested at -30°C in the Cummins, but it is anticipated that the extra 5°C reduction in test temperature would not have caused a dramatic increase in startup difficulties for Fuels A, B, C, D or F. Thus, it appeared that sensitivity to synthetic distillate components was more important than to ambient temperature down to -30°C, for the Cummins.

No plot was made for the Mack E6-350, because the truck started up very easily on the six fuels down to -25°C, and even at -30°C it started on Fuel E in just 2 seconds. Throughout the AWCD program, the Mack's startability remained remarkably insensitive to fuel quality and to ambient temperature. The Detroit Diesel 8V92 was a complete contrast to the Mack, as shown in Figure 15. At 0°C, the truck started in 1 second on each of the six fuels. At -15°C, Fuels A, B, C, D and F permitted easy starts in 8 seconds or less; Fuel E required 38 seconds, which was still a reasonably easy start but it indicated some sensitivity to synthetic distillate components. At -25°C, the truck proved very difficult to start on all fuels, requiring the hot battery and ether injection in every case. In this manner, the Detroit was much different from the other three trucks; at -25°C, the enormous ambient temperature effect masked any potential fuel quality effects. Only at -15°C was there some evidence of sensitivity to fuel quality.

To summarize, the Mack showed no sensitivity to temperature with any fuel, while the Caterpillar and Cummins showed marked sensitivity with one specific fuel each: the low back-end volatility Fuel C and the mostly synthetic Fuel E for the Caterpillar and Cummins, respectively. In contrast, the Detroit showed a very pronounced temperature effect at -25°C, which dominated any incipient fuel quality effects that were noted at -15°C. The Detroit was extremely difficult to start on all of the test fuels at -25°C. The impact of engine hardware is discussed in more detail in the following section.

#### 3.3.1.3 Engine Hardware Effects

An overview of engine hardware effects in Figure 16 shows substantial differences as the test temperature drops from 0°C to -30°C. Fuel E was chosen for this comparison, since it was the only fuel tested down to -30°C in three of the four trucks. Thus, the comparison had a fuel quality factor built in which influenced the extent of the differences observed between trucks and between temperatures. Nevertheless, the exercise was worthwhile in demonstrating the large effect of engine type at low temperature. At 0°C, all four trucks started after only 1 second of cranking. Even at -15°C, three of the trucks started after just 1 second, but the Detroit required 38 seconds of cranking with the cold-soaked battery. By -25°C, the Caterpillar and Mack still started after only 4 and 3 seconds, respectively. The Detroit's startability continued to degrade, requiring the hot battery and two injections of ether for successful startup. In addition, the Cummins exhibited startup difficulties, that required 105 seconds total cranking and use of the hot battery. At -30°C, the Mack continued to start after only 2 seconds of cranking, while the Caterpillar needed a still modest 16 seconds. The Cummins performance deteriorated further and required the hot battery and ether injection to achieve a successful start. Time and budget constraints prevented a -30°C test on the Detroit Diesel, but it is probable that the truck would have failed to start judging from its -25°C performance.

Obviously, the Detroit was unique in its startup performance; it was the only truck to experience any startup difficulty, albeit modest, at -15°C (Fuel E), and to require the hot battery and ether injection for all tests at -25°C. The Mack's performance was at the other extreme; no combination of fuel and test temperature in this program resulted in even a moderate deterioration in startability. A summary of some engine fluid temperatures in Table 31 offers an explanation for most of these differences. Coolant temperature for the Caterpillar at startup on Fuel E ranged between 41°C and 20°C, for tests at 0°C and -30°C ambient temperatures, respectively. Even at the lowest temperature, this truck started after only 16 seconds of cranking. The Mack's coolant heater was even more efficient, and startup coolant temperatures ranged from 56°C to 29°C. In fact, the coolant temperature in the Mack at -30°C ambient was equivalent to that of the Caterpillar at -15°C ambient. Consequently, it is not surprising that the Mack started so easily down to -30°C. The substantially lower oil sump temperatures recorded for this truck were believed due to the oil cooler, but the XD-3 10W30 oil startup temperature limit of -28°C was not approached and adequate cranking rpm was achieved in all the Mack tests.

Startup coolant temperatures in the Cummins ranged from 52°C to 30°C. However, despite higher coolant temperatures than the Caterpillar at each of the four test temperatures, the Cummins was much more difficult to start at -25°C and -30°C. The cause of this difference, despite apparently adequate coolant temperatures, is probably linked to the dissimilar fuel systems. Both the Caterpillar and Mack have high pressure fuel systems that push the fuel through a fine secondary filter; the Cummins has a low pressure fuel system that sucks fuel through a fine primary filter. Thus, the Cummins fuel delivery system is more sensitive to fuel viscosity increases as the fuel temperature is lowered and insufficient fuel is delivered to each injector. In addition, reference to the engine specifications of Table 3 shows that the Cummins has the lowest compression ratio, which would contribute to starting difficulties at low ambient temperatures. Thus, at equivalent test temperatures, the low pressure fuel system and low compression ratio account well for the poor cold starting performance of the Cummins, compared to the Caterpillar and Mack.

The Detroit Diesel has by far the highest compression ratio and also has a high pressure fuel system. Nevertheless, the truck showed the most severe deterioration in startability on all six test fuels, as the test temperature was lowered to -25°C. The coolant temperatures in Table 31 offer a plausible explanation for this poor performance. At -15°C ambient, the 22°C coolant temperature was already lower than that of any of the other trucks at -25°C ambient; but the high fuel line pressure and high compression ratio compensated and easy startups were achieved, in general. However, at -25°C ambient, the 15°C coolant temperature asserted its influence and caused a severe deterioration in startability. No -30°C tests were performed with the Detroit, but it is likely that the extra 5°C temperature reduction would have resulted in total failures with at least some of the six fuels. It is interesting to note that Detroit Diesel's recommended minimum coolant temperature for cold weather starting is 38°C, a temperature that was only exceeded for certain 0°C tests in this program.

In summary, the Caterpillar and Mack achieved easy starts down to -30°C on Fuel E, while both the Cummins and Detroit Diesel experienced starting difficulties at -25°C and lower. The important factors accounting for these performance differences were fuel line pressures, compression ratios and coolant temperatures. Higher compression ratio results in higher compression temperatures, and would predict the following order for increasing startup difficulties:

Detroit Diesel < Mack < Caterpillar < Cummins

However, the startup coolant temperatures would predict the following order at any single ambient temperature:

Mack < Cummins < Caterpillar < Detroit Diesel

The high pressure fuel systems of the Caterpillar, Mack and Detroit Diesel and the low vacuum system of the Cummins would predict the following order:

Caterpillar ~ Mack ~ Detroit Diesel <Cummins

The actual observed order is shown below:

Mack < Caterpillar < Cummins < Detroit Diesel

This is close to the order predicted by the startup coolant temperatures, with the Cummins and Caterpillar changing places. As discussed above, the low pressure fuel system in the Cummins would account for the disparity. Thus, the single variable that had the most influence on cold startup performance of the four truck engines was coolant temperature, at -25°C and lower ambient temperatures. Compression ratio and fuel line pressure appeared to play important but secondary roles. It is possible that other factors also played a role, such as the differences between 2- and 4-stroke engines, but the above interpretation accounts for the experimental data.

The Phase 2 engine testing leaves no doubt as to the importance of coolant temperature to cold starting; at -25°C ambient, the Caterpillar 3406 engine failed to start with Fuels B and D, despite the use of the hot battery and ether injection. In contrast, the Caterpillar 3406 in the AWCD program started very easily at -25°C on all but Fuel C. The only significant difference between these tests, assuming small engine-to-engine variability, was the startup coolant temperatures: -25°C for the bench engine and 22-23°C for the truck-mounted engine. Such a conclusion is encouraging, in that increasing startup coolant temperatures, by use of more powerful and efficient heaters, is a relatively simple alteration of trucks already in the field. This concludes the discussion on cold starting performance. The next section deals with the influence of fuel quality, temperature and engine type on cold idle white smoke production.

### 3.3.2 White Smoke Production

As described earlier, following each successful startup, the trucks were idled for at least 15 minutes. In many instances, this idling time was longer than necessary to warm the engine prior to applying a load, but it was required to establish the magnitude of exhaust white smoke production. White smoke opacity is plotted for each test run in "group plot" C in Appendices 7 to 81, and will be of use in following the discussions on variables that influence white smoke. In addition, some extra plots have been included in the Figures section, to compare better the effects of variables such as fuel quality and engine type. The first section below discusses the effects of fuel quality and composition.

#### 3.3.2.1 Fuel Quality Effects

In Table 32, white smoke production has been reported as time to 10% smokemeter opacity, a smoke level that would be barely visible to the unaided eye. For those tests in which opacity did not drop to 10% by the end of the idle period, the opacity at 15 minutes idling has been reported. Comparison of Fuels A and B at -25°C provided an evaluation of natural cetane effects. For the Caterpillar, white smoke intensity dropped rapidly in the first few minutes on Fuel A, and read 10% opacity at about 14 minutes after startup. With Fuel B, smoke intensity dropped much more slowly and was still at 29% opacity after 15 minutes. For the Cummins, Fuel A white smoke intensity decreased in a more erratic fashion than for the Caterpillar but it did reach a moderate 16% opacity after 15 minutes. Fuel B's smoke production showed a small drop from about 80% to 65% after 5 minutes, but no further reductions occurred to the end of the 15 minute idling period. Thus, the effect of lower natural cetane was much more pronounced in the Cummins than in the Caterpillar. For the Mack, white smoke intensity dropped rapidly with Fuel A to 10% opacity after about 2 minutes; with Fuel B, opacity appeared to stabilize at about 16% after 10 minutes and remained at that level to the end of the idle period. Performance on Fuel A was extremely good and less so on Fuel B but nevertheless, the white smoke intensity with Fuel B was considerably lower than for the Caterpillar or Cummins. Short but intense bursts of white smoke were recorded for each of the five startup attempts of the Detroit on Fuels A and B. However, once successfully started, opacity dropped extremely rapidly to below 10%; in less than 1 minute with Fuel A and in 6 minutes with Fuel B. Thus, all four trucks clearly produced longer periods of high white smoke levels with Fuel B than with Fuel A. However, the differences between the fuels was most marked for the Cummins and Caterpillar, while the Mack and Detroit were very clean-burning.

A study of natural and ignition-improved cetane was possible by comparing Fuels B and D, with 36.3 and 38.1 cetanes, respectively. Reference to the Appendices shows white smoke traces that look remarkably similar, for these two fuels in the Caterpillar at -25°C. In fact, as reported in Table 32, the opacity value of 23% for Fuel D after 15 minutes was slightly better than the 29% recorded for Fuel B. However, the small difference probably is not significant and the white smoke production levels should be

considered equivalent. For the Cummins, white smoke production was substantial with both fuels, but was certainly lower with Fuel D. After 15 minutes idling, opacities were 66% and 26% for Fuels B and D, respectively. Reference to the Appendices group plots indicates idling speeds of about 500 rpm and 560 rpm for the Fuels B and D tests, respectively, and slightly higher coolant temperatures for the latter. These factors may have contributed to the lower smoke production with Fuel D. Idle roughness also was more severe for longer with Fuel B than Fuel D. For the Mack, white smoke levels were similar with the two fuels, although the rapid drop in intensity occurred earlier with Fuel B. Opacity levels stabilized between 7 and 10 minutes in the two tests and were similar by the end of the idle period. The actual opacity values of 16% and 22% for Fuels B and D, respectively, should be considered essentially equivalent and are relatively modest. For the Detroit, again smoke levels dropped rapidly after startup, but the levels remained above 10% distinctly longer with Fuel D than with Fuel B; 9 and 6 minutes, respectively. However, the 3 ether injections for the Fuel D test, compared to 2 injections for Fuel B, may have contributed to the somewhat longer high smoke period. Nevertheless, in both cases, white smoke levels dropped very rapidly compared to those of the other three trucks. In summary, the Caterpillar and Mack exhibited no significant differences in white smoke production for Fuels B and D; the Cummins and Detroit produced lower smoke levels on Fuels D and B, respectively. However, the Cummins results may have been influenced by other factors.

Comparison of the performances of Fuels A and F also provided a means to study natural and ignition-improved cetane. With natural cetanes of 42.5 and 36.3 for A and F, respectively, the 6.2 natural cetane spread is larger than the 1.0 natural cetane spread between Fuels B and D. Thus, in the A versus F comparison, the ignition improver in Fuel F had a more difficult task in attempting to compensate for the large natural cetane spread. The superimposed white smoke traces in Figure 17 show clearly that in the Caterpillar at -25°C Fuel A produced substantially less smoke. From startup, white smoke dropped very rapidly on Fuel A, while a much slower decline occurred with Fuel B. As reported in Table 32, Fuel A smoke levels dropped below 10% opacity within 15 minutes idling, while opacity was still at 30% at the end of the Fuel B's idling period. For the Cummins at -25°C, the plots in Figure 18 demonstrate that white smoke initially dropped more quickly with Fuel A than with F, but the intensities were essentially equivalent by about 10 minutes into the idle period. After 15 minutes, opacities were 16% and 21% for Fuels A and F, respectively. Thus, unlike their performance in the Caterpillar, the two fuels produced substantially different smoke levels initially, but the levels dovetailed part way through the idle period.

For the Mack, the plots in Figure 19 show extremely rapid reductions in smoke levels after no more than 3 minutes idling with both fuels. Opacity dropped below 10% after 2 minutes and 7 minutes with Fuels A and F, respectively. Although the data indicate a distinct difference in smoke production, the absolute performances were so good compared to those in the Caterpillar and Cummins that Fuels A and F were considered roughly equivalent in the Mack for all practical purposes. Once the Detroit was successfully started, the plots in Figure 20 show that smoke intensity dropped extremely quickly to below 10% opacity with both fuels. 10% opacity levels were reached in under 1 minute and 3 minutes with Fuels A and F, respectively, but again, both fuels performed so well that for all practical purposes they were considered roughly equivalent.

Thus, only the Caterpillar produced significantly higher levels of smoke with Fuel F throughout the idle period. The Cummins produced more smoke with Fuel F for only part of the idle period, while the performances of the two fuels were roughly equivalent in the Mack and Detroit. In summary, the less clean-burning engines, that inherently produce more smoke, were the only ones in this test to produce significantly more white smoke on ignition-improved Fuel F than on natural cetane Fuel A. These trucks did not perceive Fuel F to be of equivalent ignition quality to Fuel A; in other words, increase in cetane via ignition improver was not equivalent to a natural increase of a similar magnitude.

The effect of chemically raising cetane by addition of an ignition improver additive was studied by comparing base Fuel B and its ignition-improved counterpart, Fuel F. Reference to the relevant group plots in the Appendices show very similar white smoke traces for both fuels in the Caterpillar at -25°C; opacities dropped at moderate rates through the idle period and reached 30% after 15 minutes. The ignition improver had no effect in reducing smoke levels below those attributed to the base fuel, but it appeared to provide smoother idling. Interestingly, Fuel F did produce somewhat lower smoke levels than B at -15°C, such that opacity dropped below 10% after 7 minutes with Fuel F but was still at 15% with Fuel B after 15 minutes. Apparently, ambient temperature affects the effectiveness of ignition improver. This is not surprising, since at higher ambients the ASTM D-613 cetane engine does respond equally well to natural or chemical cetane increases.

For the Cummins, Fuel F smoke production dropped at a moderate rate to 21% opacity after 15 minutes. However, with Fuel B, an early reduction from about 80% to 65% opacity occurred, but then that level was maintained to the end of the idle period. Thus, the Cummins responded well to the addition of ignition improver to the base fuel. For the Mack, smoke levels dropped quickly after startup with both fuels but stabilized at a lower level on the ignition-improved fuel. Opacity dropped to 10% after 7 minutes with Fuel F, but was still at 16% after 15 minutes with Fuel B. The absolute smoke production was low for both fuels, compared to smoke production from the Caterpillar and Cummins. For the Detroit, the ignition improver caused a faster reduction in white smoke but the initial drop to about 15-20% opacity with Fuel B was so rapid anyway that the impact of the ignition improver was relatively minor. Opacities dropped to 10% after 6 and 3 minutes with Fuels B and F, respectively.

In summary, the Caterpillar saw no benefit from the ignition improver in control of smoke production, the Mack and Detroit saw some benefit but the smoke levels were low on both fuels anyway, and only the Cummins showed a large favourable response to the ignition improver. The Caterpillar showed a significant improvement with the ignition-improved fuel at a higher temperature. These results suggest the effectiveness of ignition improvers is temperature- and engine-specific.

The back-end volatility effect was studied by comparing the performances of Fuels B and C at -25°C. As discussed previously, the low back-end volatility Fuel C caused more starting difficulties than Fuel B in the Caterpillar. Following startup, white smoke levels with Fuel C remained very high for 5 minutes and then dropped slowly to only 71% after 15 minutes idling. With Fuel B, white smoke levels began dropping quickly about 1 minute after startup and reached a more modest 29% after 15 minutes. Thus, the Caterpillar's smoke production was excessive with Fuel C and dramatically higher than with the more volatile Fuel B. In contrast, the Cummins showed minimal response to the fuel volatility differences. With Fuel B, opacity stabilized after 4 minutes at about 65% to the end of the idle period, while Fuel C showed a gentle decline from an initial 95% opacity to 71% after 15 minutes idling. The Mack responded adversely to Fuel C's higher 90% point, with substantial smoke levels throughout the idle period. Smoke levels dropped more quickly with Fuel B, and the end of idle opacities were 16% and 36% for Fuels B and C, respectively.

For the Detroit, white smoke levels dropped quickly with Fuel B and somewhat more slowly with Fuel C, accompanied by severe oscillations in smoke intensity. Opacity levels reached 10% after 6 and 9 minutes on Fuels B and C, respectively, and heavy rough idle was observed for considerably longer on C than B. Unfortunately, the 8°C lower startup coolant temperature for the Fuel C test may have contributed to that run's more severe idle roughness and wide smoke intensity oscillations. However, even if the coolant temperature difference was not a significant factor, the smoke production differences were relatively small, especially in comparison with smoke levels in the other three trucks mid-way through the idle period.

In summary, smoke levels increased significantly with Fuel C in the Caterpillar and Mack; absolute smoke levels were very high and low in the Cummins and Detroit, respectively, but the differences between the two fuels in each truck were small. In other words, only the Caterpillar and Mack proved sensitive to back-end volatility.

Conventional versus synthetic distillate component effects were assessed using Fuels C and E at -25°C. The superimposed white smoke traces in Figure 21 for the Caterpillar show an easier start with Fuel E and much lower smoke levels throughout the idle period. At the end of the idling period, opacity levels were 71% and 26% for Fuels C and E, respectively. Unfortunately, the Caterpillar's smoke production was most sensitive to back-end volatility and the 20°C higher 90% point of Fuel C probably accounts for a significant portion of the large difference in smoke levels between the two fuels. However, on an absolute basis, the smoke trace for Fuel E is very similar to those of the Fuels B, D and F, and the 26% opacity value after 15 minutes idling is comparable with the 23-30% values recorded for B, D and F. Thus, the conclusion is that the high synthetic distillate content of Fuel E had no effect on white smoke levels in the Caterpillar. At 0°C and -15°C, smoke levels were roughly equivalent for the two fuels, supporting the above conclusion. As shown in Figure 22, following a more difficult start with Fuel E, smoke levels in the Cummins were high and roughly equivalent for

the two fuels. Opacities stabilized at about 70% at the end of 15 minutes idling, for both fuels. However, the Fuel E idle segment had to be extended to further warm the engine before the engine could be put in gear and successfully accelerated to 50 kph. Thus, smoke production for the two fuels was roughly equivalent for the first 15 minutes of idling, but the need for further idling and the associated high smoke levels made Fuel E the poorer performer. However, smoke production was comparable for the two fuels at 0°C, but significantly higher for Fuel E at -15°C. Apparently, the temperature was too mild at 0°C to detect smoke production differences and too severe at -25°C; the results at -15°C indicate clearly more white smoke production for the mostly synthetic distillate fuel.

The Mack's white smoke traces in Figure 23 show an initially lower level for Fuel E at -25°C, but essentially equivalent stabilized levels after about 11 minutes of idling. After 15 minutes, the opacities were 36% and 32% for Fuels C and E, respectively. The early higher smoke levels for C were probably a reflection of that fuel's lower back-end volatility, a fuel property to which the Mack was observed to be sensitive. Thus, the impact of synthetic distillate on smoke levels in the Mack was small at worst. For the Detroit, the plots in Figure 24 show that Fuel E smoke levels dropped more quickly than those for Fuel C and with Fuel C there were large oscillations in smoke levels for about 8 minutes. The slightly longer idling time to 10% opacity of 9 minutes for Fuel C, compared to 5 minutes for Fuel E, may have been due to lower startup coolant temperature or Fuel C's higher 90% point. Nevertheless, the conclusion was that the synthetic distillate in Fuel E did not cause an increase in white smoke intensity or duration. Performances of the two fuels were equivalent at each of 0°C and -15°C. In summary, the mostly synthetic distillate Fuel E produced roughly equivalent levels of white smoke to Fuel C in three of the trucks most of the time. Any small differences noted for the three trucks and the large difference for the Caterpillar were attributed to Fuel C's lower back-end volatility. The major conclusion is that Fuel E did not produce higher smoke levels than a conventional distillate fuel, except in the Cummins at -15°C.

To summarize, the major fuel quality effects on white smoke production were observed to be natural cetane and back-end volatility. All four trucks produced more smoke with a drop in natural cetane, while the Caterpillar and Mack showed the only substantial smoke increases with lower fuel back-end volatility. The Cummins responded well to the addition of ignition improver to base Fuel B, while the Mack and Detroit showed smaller benefits. The Caterpillar saw no benefit for ignition improver at -25°C, but there was evidence that the additive provided smoke reduction benefits at more moderate temperatures. None of the trucks perceived chemically-derived cetane to be equal to natural cetane in controlling smoke. Finally, only at -15°C with the Cummins were higher smoke levels noted on switching from conventional diesel to a fuel composed mostly of synthetic distillate components. The effect of ambient temperature on white smoke production is discussed in the following section.

### 3.3.2.2 Ambient Temperature Effects

The impact of varying ambient temperatures on smoke production was studied for all four trucks using Fuel E. Ambient temperature effects on smoke production from the Caterpillar were pronounced, as shown in Figure 25. Smoke levels dropped substantially through the idle period but were still significant at -15°C and lower. The data reported in Table 33 show a large increase in smoke upon dropping from 0°C to -15°C; opacities were 10% at 9 minutes and 19% at 15 minutes, respectively. The increase in 15 minute opacity value to 26% was reasonably small upon dropping from -15°C to -25°C. However, a further 5°C drop to -30°C, caused a much larger increase in the 15 minute opacity, to 44%. These data indicated that the Caterpillar was most sensitive to ambient temperature at and below -25°C. The plots in Figure 26 and data in Table 33 demonstrate that the Cummins' smoke production increased rapidly with a drop in temperature from 0°C to -15°C. Opacity values were 10% after 12 minutes at 0°C but 36% after 15 minutes at -15°C. Further temperature reductions resulted in very little drop in smoke level through the idle period; in fact, at -25°C and -30°C, the idle periods were extended because the Cummins had not warmed sufficiently to permit acceleration to 50 kph. After the initial 15 minutes idling, opacity levels were 67% and 90% at -25°C and -30°C, respectively. Thus, the Cummins' smoke production increased rapidly at sub-zero temperatures.

As Figure 27 and Table 33 data illustrate, the Mack truck showed no smoke at 0°C and only very modest levels at -15°C. In fact, opacity levels hovered near 10% from only a few seconds after startup at -15°C, but actually dropped below 10% after 4 minutes. Even at -25°C, opacity dropped quickly to about 30% after only 3 minutes of idling and eventually stabilized at that level to the end of the idle period. However, the short temperature reduction to -30°C resulted in a massive increase in smoke levels, which only dropped marginally through the idle period to a final value of 93% after 15 minutes. Obviously, the Mack's smoke production was only moderately sensitive to temperature down to -25°C, below which a dramatic increase in sensitivity occurred. The Detroit was a difficult truck to start as discussed previously but, if the complicating effect of multiple starts at -15°C and lower is ignored, it is obvious from Figure 28 that it was by far the cleanest burning truck in this program and showed only a small sensitivity to temperature down to -25°C. As reported in Table 33 and shown clearly in Figure 28, the opacity dropped below 10% within a few seconds after startup at 0°C. At -15°C and -25°C, more smoke was produced but even so the levels dropped very quickly below 10% opacity, after 3 and 5 minutes, respectively.

In summary, the Caterpillar and particularly the Cummins showed substantial increases in smoke with each reduction in ambient temperature below 0°C. The Detroit was easily the cleanest burning engine and showed only very small increases in smoke production down to -25°C. The Mack proved to be a relatively clean-burning engine down to -25°C, but produced such enormous amounts of smoke at -30°C that it was comparable to the Cummins' output at that temperature. The following section addresses the effect of engine hardware on white smoke production.

### 3.3.2.3 Engine Hardware Effects

Each of the six test fuels were compared for white smoke production at -25°C in all four trucks. As expected, considerable truck-to-truck variations were noted. Furthermore, the plots in Figures 29, 30, 31 and 32 and the summarized data in Table 34 demonstrate that the truck response variability was fuel dependent. For example, with Fuel C the order of decreasing smoke production during the 15 minute idle period was Cummins > Caterpillar >> Mack >> Detroit. The 15 minute opacity values for the Cummins and Caterpillar were equal, but the Cummins' smoke level appeared to be dropping much more slowly than that of the Caterpillar and so was ranked a heavier smoking truck. The Mack's smoke production was considerably lower than either, while the Detroit's smoke production started high but dropped rapidly to negligible levels before the end of the idle period. Thus, with Fuel C at -25°C, large differences in smoke production were observed between the four trucks. In contrast, as shown in Figure 30, differences were smaller with Fuel D, and the order of decreasing smoke production was Cummins ~ Caterpillar ~ Mack > Detroit. The performances of the first three trucks were judged roughly equivalent since, although initial rates of smoke reduction were different, the smoke levels were changing little by the end of the idle period and opacity values were similar. Once again, the Detroit's smoke levels dropped rapidly to negligible levels before the end of the idle period. Thus, three of the four trucks exhibited roughly equivalent smoking tendencies with Fuel D.

Fuel A, like D, tended to lessen differences between the trucks' smoke production. The Cummins was the heaviest smoker still, followed by the Caterpillar, but the differences were relatively small towards the end of the idle period, as shown in Figure 31. The performances of the Mack and Detroit were very similar, smoke levels dropping to negligible levels in 2 and 1 minutes, respectively. With Fuel B (Figure 32), significant differences were apparent but were not as pronounced in some two truck comparisons as with Fuel C. Overall, the order of decreasing smoke production was again

Cummins > Caterpillar > Mack >Detroit

The order for Fuel E was Cummins >> Caterpillar ~ Mack >> Detroit. Smoke production for the Mack initially was more rapid than for the Caterpillar but smoke levels were similar by the end of the idle period. Interestingly, the ignition improver added to Fuel B, resulting in Fuel F, had a large beneficial effect on smoke production of the Cummins but no effect for the Caterpillar. This resulted in the following order for decreasing smoke production

Caterpillar ~ Cummins > Mack > Detroit

The impact of ignition-improved Fuel F was very small for the Mack and Detroit, compared to the smoke production with Fuel B.

In summary, the Cummins and Detroit were generally the heaviest and lightest smoking engines, respectively, in this program. The Caterpillar and Mack were sandwiched between these two extremes. However, the degree of smoke production difference, especially between the Cummins, Caterpillar and Mack, was very dependent upon the fuel. For example, smoking tendencies for these three trucks with the low base cetane Fuel D were roughly equivalent; with the low back-end volatility Fuel C, large differences between trucks were observed. The Mack responded adversely to Fuel E and resulted in equivalent smoke production to the usually heavier-smoking Caterpillar. The Caterpillar showed no response to the ignition improver in the Fuel F, which resulted in slightly heavier smoking than for the Cummins with Fuel F.

The general order observed for decreasing smoke production was in line with the increasing compression ratio: Cummins < Caterpillar < Mack < Detroit. It was probable that startup coolant temperatures influenced smoke intensity, particularly in the early stages of the idle period, but the major influence of compression ratio tended to assert itself by the end of 15 minutes of idling. However, few truckers would idle for 15 minutes after a cold start, since the engine warms much more quickly under load. Thus, the influence of startup coolant temperature on initial smoke levels would be more important in the field, and presents an opportunity to reduce smoking with the use of more powerful/efficient block heaters. This concludes the discussion on cold idle white smoke production. The next section deals with the effects of engine design, fuel quality and ambient temperature on driveability.

### 3.3.3 Driveability

Adequate driveability in this test was defined as the ability to accelerate smoothly to 50 and 90 kph, maintain each of the two constant speeds with no difficulty, and complete the drive sequence. Most of the test runs were rated in the pass category, as listed in Table 35. In fact, all test runs on the Caterpillar and Detroit Diesel were assigned pass ratings, with only rough idle observed as an operability debit on a few occasions. Generally, the Mack exhibited good driveability, with only an occasional engine surging phenomenon during idle. However, at -30°C with Fuel E, some initial hesitation was observed for the first acceleration to 50 kph. The hesitation is not obvious from the road speed trace in Appendix 63, but it was observed by the truck driver and a borderline pass rating was assigned accordingly.

In contrast to the above three trucks, the Cummins experienced driveability problems at -25°C on all but Fuels A and F. The results at -25°C for Fuels A and B in Table 35 are pass and borderline pass ratings, respectively. The truck experienced sluggish acceleration to 50 kph with Fuel B but was able to complete the drive sequence. Comparison of the two road speed profiles in Figure 33 shows a small lag for the Fuel B run throughout the acceleration. As plotted, the lag is small but was noticeable to a professional truck driver. The corresponding engine speed traces (rpm+20 to fit the scale) in Figure 33 demonstrate the poorer idle quality observed for the truck with Fuel B.

Driveability performance comparisons of Fuel B with Fuels C, D and E were interesting, because all four were of similar cetane but differed significantly in other aspects. A borderline fail rating was assigned to the -25°C run with Fuel C. The road speed profiles for Fuels B and C in Figure 34 show clearly the severe loss of power for the Fuel C run, during the acceleration to 50 kph. The truck was able to reach and maintain the two steady-state speeds and complete the drive sequence. However, the loss of power was severe enough that such occurrences in the field would cause customer complaints. The truck driver noticed some engine surging with Fuel D during the initial acceleration, and a borderline pass rating was assigned accordingly. However, the ignition improved fuel was not significantly different from its natural cetane counterpart, Fuel B, in driveability performance. Considerable difficulty was experienced at -25°C with Fuel E, as illustrated by comparison with Fuel B in the engine speed profiles of Figure 35. Engine speed profiles were chosen to show more clearly the difficulty experienced in raising engine speed sufficiently to engage the transmission. A significantly rougher idle was experienced with Fuel E, the truck failed to accelerate after 15 minutes idling and a further 6 minutes of idling was needed. Subsequently, the acceleration to 50 kph was poor and a constant speed could not be maintained for the first 5 minutes of that segment. The Fuel E run was rated a borderline fail, since such extreme operational problems would raise customer complaints.

At -30°C, performance with Fuel E was so poor that the drive sequence could not be completed, and a fail rating was recorded. The engine speed profiles in Figure 36 show that the idle quality at -30°C was even poorer than that for the same fuel at -25°C. After 15 minutes, the engine was barely idling at about 520 rpm; it stalled upon trying to accelerate and would not accelerate above 2 kph after an immediate restart. Further idling to a total of 38 minutes was necessary to achieve a high enough idle speed that allowed the driver to remove his foot from the accelerator pedal. Subsequently, the driver was able to accelerate to abut 40 kph but could not increase speed further and so aborted the run.

Fuel filter plugging by wax or foreign material was not observed in the Fuels C and E tests, as evidenced by the appropriate fuel vacuum profiles in the Appendices. However, comparison of inspections in Table 5 revealed that viscosity varied greatly between Fuels B, C, D and E; about 2.0 cSt for B and D, and about 3.2 cSt for C and E. A potential sensitivity to fuel viscosity by the Cummins was mentioned earlier in Section 3.3.1.3, in connection with startup performance. This sensitivity may be due to poorer fuel spray pattern in the relatively low compression ratio combustion chamber, or to impeded fuel flow to the injectors. This theory would account for the lack of available power to accelerate adequately, or to achieve and maintain constant 50 kph and 90 kph speeds. In addition, the road speed profiles at -25°C and -30°C for the high viscosity fuels show considerable uneven oscillation around the constant speed values. These observations are consistent with a problem in delivering fuel smoothly to the injectors or in developing smooth combustion. Fuels A and F gave no driveability problems, despite a slightly higher viscosity for Fuel A than for B, D, and F. Apparently, the higher cetane (natural for Fuel A and additive-derived for F) improved combustion enough to avoid the sluggish acceleration observed with Fuels B and D.

In summary, the Caterpillar and Detroit Diesel exhibited no driveability problems with any of the fuels down to -25°C, or with Fuel E at -30°C. The Mack exhibited good driveability also, down to -25°C, but some initial hesitation in the acceleration to 50 kph was experienced with Fuel E at -30°C. No driveability problems were experienced for the Cummins down to -15°C. However, it exhibited severe driveability problems with Fuel C at -25°C and with Fuel E at -25°C and -30°C. The driveability was so poor in these cases that the ratings were either borderline fail or fail. High fuel viscosity was suggested as the cause of the poor performances of Fuels C and E. The fuel sensistivity of the Cummins may have reflected its relatively low compression ratio and/or its low vacuum fuel system. Sluggish acceleration experienced with Fuels B and D at -25°C may have been due to poor combustion, since no such problem occurred with higher cetane Fuels A and F. Engine design was more significant than the fuel quality range for driveability performance, as concluded in the discussion earlier on cold starting. The next section deals with the effects of fuel quality, engine design and ambient temperature on fuel consumption.

### 3.3.4 Fuel Consumption

Fuel consumption was monitored in the AWCD truck testing, using the fuel cart referred to earlier. Although fuel consumption was monitored continuously, only that data recorded during three consecutive 5 minute intervals at the ends of the 50 kph and 90 kph segments were used for analysis. This approach was used to allow engine fluid temperatures an opportunity to stabilize. However, temperature profiles such as those in Appendix 7A, showed that none of the important engine fluid temperatures stabilized at 50 kph and only oil sump and coolant temperatures apparently stabilized during the 90 kph segment. Transmission and differential temperatures continued to increase to the end of the drive sequence. These engine fluid temperatures strongly influence fuel consumption and in a test program specific to fuel economy they would need to be stable. The lack of engine fluids temperature stability imposed substantial errors on the fuel consumption data. Unfortunately, there was no means to estimate the value of experimental error since duplicate independent data were not obtained.

The major objective of the program was to study the effects of fuel quality, etc. on cold starting, warmup and driveability; fuel consumption was not a primary parameter, and the test methodology was developed accordingly. Thus, no claims for statistical significance can be made and the data may be used only to suggest trends at best. Nevertheless, standard deviations were calculated for the mean of the second and third 5 minute intervals in each constant speed segment; but they are not a true measure of experimental error, and should be viewed as a rough estimate of the lowest possible value for the true experimental error.

Mean fuel consumption values and standard deviations are listed for all test runs in Table 36. Generally, the standard deviations were smaller for the 90 kph data, reflecting the influence of relatively stable coolant and oil sump temperatures and operation at rated engine speed for the 90 kph segments. The possible impacts of engine design, air temperature and fuel

quality are illustrated by specific comparisons in Table 37. A comparison of engine models with Fuel B at 0°C, showed the Detroit Diesel as the heaviest fuel burner by far at 50 kph, with the Mack and Cummins proving to have much lighter appetites. The more important data were at 90 kph, since highway trucks consume the largest proportion of fuel at speeds of at least 90 kph. The Detroit Diesel showed a small fuel consumption increase, while the other three increased substantially. The trucks could be grouped into two fuel consumption categories: 49-50 ℓ/100 km for the Caterpillar and Detroit Diesel, and 43-45 ℓ/100 km for the Cummins and Mack. Differing model years (1981/82 for Caterpillar and Detroit Diesel versus 1985 for Cummins and Mack) and gear ratios would be expected to have major influences on fuel consumption. Accordingly, it is not possible to make any firm conclusions on the effect of engine design on fuel consumption in this truck test.

The potential impact of ambient temperature is illustrated using Fuel D in the Cummins and Fuel E in the Detroit Diesel. Lowering temperature would be expected to cause increased fuel consumption due to increased lubricant viscous drag, increased wind resistance and increased tire rolling losses. The Cummins experienced fuel consumption increases of about 5% at 90 kph, upon dropping ambient temperature from 0°C to -25°C. The fuel consumption differences may not have been statistically significant for the reasons discussed earlier, but the general trend to increased fuel consumption with lower temperature was consistent with expectations. Similarly, the Detroit Diesel trend was to increased fuel consumption with Fuel E at 90 kph, as temperature was lowered. However, the increase observed was smaller than that for the Cummins, and the probability of statistical significance was lower.

The effect of fuel quality is illustrated with the Cummins at -15°C. Theoretically, volumetric fuel consumption should correlate well with fuel density, unless a fuel is of such poor ignition quality that combustion is hampered significantly. The 90 kph data in Table 37 generally reflect such a dependence on density. Fuels C and E resulted in substantially lower fuel consumption than the other four fuels, although, again the difference cannot be assessed for statistical significance. The 50 kph data show no such trend and probably are less trustworthy for the reasons discussed earlier. The Caterpillar 3406 engine testing in Phase 2 similarly detected a volumetric fuel consumption dependence on density; fuel consumption decreased from Fuels B to E to C, three fuels of similar cetane.

In summary, the primary focus of the AWCD program was on cold starting, white smoke and driveability, which dictated a test design unsuited to fuel economy. Thus, fuel consumption measurements were not optimum and the results could only be used to suggest possible trends. At 90 kph, the Caterpillar and Detroit Diesel appeared to burn considerably more fuel than the Cummins and Mack. Since the late 1970's, the engine manufacturers have made progressive fuel economy increases a high priority, and the differences detected here simply may reflect model year differences: the Caterpillar and Detroit Diesel are 1982 and 1981 engine models, while the other two engines are 1985 vintage. In addition, varying gear ratios may have contributed

significantly to the trucks' fuel consumption differences. As expected, fuel consumption trended higher as air temperature was lowered, although the magnitude of the effect appeared to vary with engine model. Finally, volumetric fuel consumption generally decreased with higher fuel density, at least at 90 kph. However, the fuel consumption dependence on fuel quality measured in the Phase 2 engine testing was more reliable than the AWCD results. This concludes the discussion on fuel consumption.

## 4. CONCLUSIONS

Six test fuels were blended, mostly from conventional refinery diesel components, to meet the objectives of this program's fuel matrix. The fuels' qualities and compositions allowed the effects of variations in natural cetane, chemically enhanced cetane, back-end volatility, and conventional versus synthetic crude source to be addressed in heavy duty diesel engines. In Phase 2, the six fuels were tested under cold and hot bench engine conditions; in Phase 3, the fuels were evaluated for cold weather operability in four Class 8 tandem axle trucks.

The effects of fuel properties on the Caterpillar 3406 engine performance are summarized in Table 38. Increasing fuel cetane, either naturally or via the use of cetane improver, slightly improved startability and reduced white smoke production. After start-up, idling was smoother with higher cetane fuels due to shorter ignition delay. However, when the engine was fully warmed-up and operated at intermediate or higher power levels, higher fuel cetane showed no improvement in black smoke, hydrocarbon and carbon monoxide emissions. On the other hand, nitrogen oxide emissions and cylinder pressure rise were reduced with increase in the fuel cetane. Higher fuel cetane reduced specific fuel consumption (g/kW-hr). However, Fuels A and B showed very similar volumetric fuel consumption (L/kW-hr), because of the lower density of high cetane relative to low cetane fuels.

Comparison of a 35.3 cetane base fuel ignition-improved to 38.1 cetane and a natural 36.3 cetane fuel of similar volatility demonstrated similar performances in starting, exhaust emissions and fuel economy.

Decrease in the back-end volatility (increased $T_{90}$) showed no effect on startability and ignition delay, but white smoke production was increased. When the engine was warmed up, back-end volatility did not affect black smoke and nitrogen oxides emissions, but hydrocarbon emissions were reduced and carbon monoxide emissions were increased slightly. Increase in the $T_{90}$ showed no effect on the specific fuel consumption, but the volumetric fuel consumption would be reduced if the fuel density increased with decrease in the back-end volatility.

Comparison of a conventional fuel and a fuel containing large amounts of synthetic components showed slightly lower nitrogen oxide emissions for the mostly synthetic fuel. Other performance areas, such as startability, white smoke, black smoke, hydrocarbon and carbon monoxide emissions, and fuel economy, were not affected.

In summary, within the fuel matrix studied, fuel properties did not dramatically affect engine performance in the areas of low temperature startability, gaseous emissions, and fuel economy. Thus, changing fuel property specifications to meet performance requirements might not be a very effective approach.

In the AWCD low temperature testing, the general conclusion on cold startability was that each of the four trucks mostly showed only minor sensitivity to substantial changes in fuel quality. The effects of natural cetane, ignition improver and natural versus ignition-improved cetane were negligible. The few exceptions observed were for individual truck-fuel combinations. For example, the Caterpillar's startup performance at -25°C degraded significantly with the high 90% point Fuel C, and the Cummins' performance was poor with mostly synthetic Fuel E. The Mack, Caterpillar and Cummins generally showed only minor changes in startup performance as test temperature was varied from 0°C to -30°C. In contrast, the Detroit Diesel exhibited a pronounced temperature sensitivity; at -25°C, the truck was so difficult to start that any possible fuel quality effects were completely masked. Engine design and its influence on startability was the most significant variable in this AWCD program. The Mack achieved easy starts down to -30°C, while the Caterpillar and Cummins had difficulties starting at -25°C with Fuels C and E, respectively. The Detroit proved extremely difficult to start on all six fuels at -25°C. The single most important engine variable accounting for these differences was startup coolant temperature at -25°C ambient and lower. Differences in compression ratios and fuel systems were believed to have secondary effects.

Natural cetane and back-end volatility were fuel parameters that had major influences on white smoke production in the majority of the trucks. Only the Cummins showed a large reduction in smoke production with the addition of ignition improver, although none of the trucks recognized chemically-enhanced cetane to be the equal of natural cetane. Synthetic crude-derived distillate components did not cause increased smoking behaviour at low temperature in any of the trucks. The effect of ambient temperature was truck-specific; the Caterpillar and Cummins produced substantially greater amounts of smoke with each successively lower temperature below 0°C. The Mack produced significant but still moderate increases in smoke between 0°C and -25°C, and was a relatively clean-burning engine. However, at -30°C with Fuel E, its enormous increase in smoke levels made it comparable to the Cummins. The Detroit was by far the cleanest burning engine and exhibited very small increases in smoke production down to -25°C.

In general, the order for decreasing smoke production was: Cummins > Caterpillar > Mack > Detroit, which was in line with increasing compression ratio. However, the degree of difference for the Cummins, Caterpillar and Mack was very dependent on the fuel. For example, the differences in smoke production between these three trucks was large for the high 90% point Fuel C, but small for the low base cetane Fuel D. Startup coolant temperature was considered to be a secondary influence, particularly during the first few minutes of idling. Thus, more powerful and efficient coolant heaters might help control initial smoke production as well as cold startability.

No driveability problems were encountered with the Caterpillar, Mack or Detroit Diesel down to -25°C, although the Mack exhibited some initial hesitation during the first acceleration with Fuel E at -30°C. The Cummins had no problems down to -15°C, but exhibited varying degrees of driveability problems at -25°C and -30°C. Fuels C and E were either borderline or total failures at these temperatures, and the fuels' high viscosities may have been implicated in the poor driveability. The sensitivity of the Cummins may have been due to a relatively low compression ratio and/or a low vacuum fuel delivery system. Sluggish acceleration at -25°C with Fuels B and D may have been the result of poor combustion, since no such problem occurred with higher cetane Fuels A and F. Fuel consumption at 90 kph constant speed appeared considerably greater for the Caterpillar and Detroit Diesel, which may have reflected their earlier model years compared to the Cummins and Mack. However, the differing gear ratios of the trucks may have had a large influence on fuel consumption. Fuel consumption trended higher with decreasing air temperature, although the magnitude of the effect appeared to vary with engine model. As expected, fuel consumption appeared to drop as fuel density increased, although the fuel quality-fuel consumption relationship was measured more reliably in the Phase 2 Caterpillar 3406 engine testing.

To summarize, engine design had by far the largest influence on low temperature startability, cold idle white smoke production and driveability. Fuel quality effects on startability, within this program's matrix, were generally minor, with very few exceptions. Fuel quality effects on white smoke production were substantial, particularly natural cetane and back-end volatility. Chemically-enhanced cetane was seen not to be the equivalent of a natural cetane increase in controlling white smoke, and a mostly synthetic fuel generally did not produce more smoke than its conventional counterpart. Fuel quality effects on driveability were only important in the Cummins at -25°C or lower; high viscosity dramatically worsened driveability and lower cetane apparently caused minor problems. Conclusions concerning fuel consumption were difficult to make, since the test methodology was not established specifically for that variable.

This report is the final version, in accordance with EPCR's contract with DS&S.

## 5. REFERENCES

(1) DSS File Number: 23216-2-6010.

(2) "Diesel Fuel Quality Trends in Canada", D.E. Steere and T.J. Nunn, SAE 790922, October 1-4, 1979.

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## 6. TABLES

## TABLE 1

## TEST FUEL SPECIFICATIONS

| Specification | Fuel A | B | C | D | E | F |
|---|---|---|---|---|---|---|
| Minimum Flash Point, °C | 40 | | | | | |
| Cloud/Pour Point, °C | Appropriate for tests down to -25°C. | | | | | |
| Viscosity at 40°C, cSt | 1.8 to 2.8 for Fuels A, B, D and F; to 3.2 max for Fuels C and E. | | | | | |
| ASTM D-86 Distillation, °C: | | | | | | |
| 10% Point | 190-215 | | | | | |
| 90% Point, min | 290 | 290 | 340 | 290 | 310 | 290 |
| max | 320 | 310 | 360 | 310 | 340 | 310 |
| Sulphur, wt% | 0.5 max | | | | | |
| Copper Corrosion, 3 hours at 100°C | 1 max | | | | | |
| Rams. 10% Carbon Residue, wt% | 0.2 max | | | | | |
| Water and Sediment, wt% | 0.05 max | | | | | |
| Cetane (Average of 3 Engines): | | | | | | |
| min | 42 | 36 | 36 | 36 | 36 | 40 |
| max | 43 | 38 | 38 | 38 | 38 | 41 |
| Composition, vol%: | | | | | | |
| Cracked Gas Oils | 5-15 | 25-40 | 25-40 | 25-40 | As Required | 25-40 |
| Synthetic Crude Source | 0-10 | 0-15 | 0-15 | 0-15 | >50 | 0-15 |
| Aromatics (Approximate) | 20 | 30 | 25 | 35 | 35 | 30 |

TABLE 2

CATERPILLAR 3406 ENGINE SPECIFICATIONS

| | |
|---|---|
| Number of Cylinders | In-Line 6 |
| Aspiration | Turbocharged, Aftercooled |
| Principle of Operation | 4-Cycle, Direct Injection |
| Rated HP | 310 |
| Compression Ratio | 14.5:1 |
| Rated RPM | 1800 |
| Peak Torque | 1478 N-m (at 1200 RPM) |
| Bore/Stroke (mm) | 137/165 |
| Displacement (L) | 14.6 |

TABLE 3

TEST TRUCK DESCRIPTION

| Engine Model | Caterpillar 3406 | Cummins NTC-400 | Mack E6-350 | Detroit Diesel 8V92-TA |
|---|---|---|---|---|
| Rated Horsepower | 400 at 2100 rpm | 400 at 2100 rpm | 350 at 1800 rpm | 435 at 2100 rpm |
| Displacement, litres | 14.6 | 14.0 | 11.0 | 12.1 |
| Engine Cycle | 4-Stroke DI | 4-Stroke DI | 4-Stroke DI | 2-Stroke DI |
| Turbocharged | Yes | Yes | Yes | Yes |
| Compression Ratio | 14.5:1 | 14:1 | 15:1 | 17:1 |
| Chassis Builder | Freightliner | International | Mack | GMC |
| Model Year | 1982 | 1985 | 1985 | 1981(1) |
| Odometer, km | 501,000 | 107,000 | 91,000 | 69,000(1) |
| Transmission | Fuller RT-14615 | Fuller RT-11610 | Mack T-2090 | Fuller RT-12509 |
| Block Heater, watts | 2240 | 2250 | 2250 | 2000 |
| Oil Pan Heater, watts | 500 | 500 | 500 | 500 |

(1) Rebuilt engine, with 400,000 km on the chassis.

## TABLE 4

## AWCD MONITORED TEST PARAMETERS

| Parameter | Sensing Device Location | Test Run Accumulation Rate(1) |
|---|---|---|
| Temperature | Fuel Drum Bottom | 5/minute |
| | Fuel Drum Middle | 5/minute |
| | Fuel Filter Inlet | 5/minute |
| | Fuel Filter Outlet | 5/minute |
| | Heat Exchanger Outlet | 5/minute |
| | Fuel Return Line | 5/minute |
| | Oil Pan | 5/minute |
| | Engine Block (Coolant) | 5/minute |
| | Engine Air Intake | 5/minute |
| | Transmission | 5/minute |
| | Front Differential | 5/minute |
| | Rear Differential | 5/minute |
| | Exhaust | 5/minute |
| | Test Cell and Presoak (Air) | 5/minute |
| Pressure | Primary Fuel Filter Inlet(2) | 5/minute |
| | Secondary Fuel Filter Inlet | 5/minute |
| | Secondary Fuel Filter Outlet | 5/minute |
| Exhaust Smoke Opacity | Exhaust Extension Pipe | 1/second |
| Battery Voltage | Battery | 1/second |
| Engine Speed | Bell Housing | 1/second |
| Road Speed | Dynamometer | 1/second |
| Wind Speed | Fan | 1/second |
| Fuel Consumption | Fuel Cart | 1/second |

(1) Overnight temperatures monitored at 5/hour.
(2) Not applicable for Cummins NTC-400 fuel system.

## TABLE 5

## TEST FUEL INSPECTIONS

| Inspection | Fuel A | B | C | D | E | F |
|---|---|---|---|---|---|---|
| Flash Point, °C | 64.0 | 56.0 | 62.0 | 58.0 | 58.0 | 56.0 |
| Cloud Point, °C | -27 | -26 | -26 | -27 | -32 | -26 |
| Pour Point, °C | -42/-45 | -48/-51 | -54/-57 | -48/-51 | -48/-51 | -48/-51 |
| Viscosity at 40°C, cSt | 2.20 | 1.99 | 3.17 | 1.98 | 3.27 | 2.04 |
| Density at 15°C, kg/ℓ | 0.8465 | 0.8612 | 0.8804 | 0.8633 | 0.8715 | 0.8615 |
| ASTM D-86 Distillation, °C: | | | | | | |
| IBP | 180 | 166 | 148 | 160 | 150 | 166 |
| 5% | 208 | 188 | 194 | 185 | 190 | 185 |
| 10% | 215 | 197 | 210 | 195 | 206 | 195 |
| 50% | 252 | 247 | 283 | 244 | 276 | 245 |
| 90% | 296 | 306 | 345 | 305 | 325 | 303 |
| 95% | 310 | 325 | 356 | 325 | 335 | 320 |
| FBP | 317 | 333 | 356 | 333 | 341 | 329 |
| Cetane Number: | | | | | | |
| ARC* | 41.8 | 36.1 | 36.7 | 38.2 | 36.2 | 41.6 |
| NRC* | 42.9 | 36.0 | 35.6 | 37.5 | 35.7 | 40.6 |
| PRD* | 42.7 | 36.9 | 35.2 | 38.7 | 35.0 | 40.6 |
| Average | 42.5 | 36.3 | 35.8 | 38.1 | 35.6 | 41.0 |
| CGSB Cetane Index | 42.6 | 36.2 | 37.1 | 34.9 | 38.3 | 36.5 |
| CN by $^1$H NMR | 44.6 | 37.1 | 37.7 | 35.4 | 39.7 | 37.5 |
| Ethyl DII-3, vol/vol, ppm | 0 | 0 | 0 | 500 | 0 | 1000 |
| Sulphur, wt% | 0.229 | 0.209 | 0.211 | 0.201 | 0.117 | 0.219 |
| **MCR, % | <0.01 | <0.01 | <0.01 | 0.01 | <0.01 | 0.01 |
| Cu Corrosion, 3 hr at 100°C | 1a | 1a | 1a | 1a | 1a | 1a |
| Water, vol/vol, ppm | 98 | 58 | 55 | 67 | 51 | 61 |
| Sediment, mg/100 ml | 0.36 | 0.22 | 0.60 | 0.22 | 0.16 | 0.08 |
| Composition, vol%: | | | | | | |
| Cracked Gas Oils | 5 | 29 | 25 | 35 | 5 | 29 |
| Synthetic Crude Source | 0 | 0 | 14 | 0 | 71 | 0 |
| Aromatics (wt%) | 33.6 | 39.8 | 44.5 | 37.0 | 46.4 | 41.8 |

* ARC - Alberta Research Council
NRC - National Research Council
PRD - Products Research Division, Exxon Research & Engineering

** Micro Carbon Residue

TABLE 6

CRANKING TIME TO START CATERPILLAR 3406 ENGINE (IN SECONDS)

| Starting Temp., °C | Fuel A | Fuel B | Fuel C | Fuel D | Fuel E | Fuel F |
|---|---|---|---|---|---|---|
| 20 | <2 | <2 | <2 | <2 | <2 | <2 |
| 0 | 3 | 12 | 10 | 9 | 7 | 5 |
| -15 | 90 | 120* | 120* | 120* | 120* | 120* |
| -25 | 150* | No Start After 180 | 180* | No Start After 180 | 180* | 180* |
| | | | Cranking RPM** | | | |
| -15 | 230 | 230 | 230 | 230 | 230 | 230 |
| -25 | 240 | 240 | 240 | 260 | 240 | 260 |

* Note: Ether injection after 90 seconds.

** Cranking RPM at 20°C and 0°C not determined because engine started very quickly. The slight increase in cranking RPM at -25°C relative to -15°C is not clearly understood.

TABLE 7

WHITE SMOKE PRODUCTION FROM CATERPILLAR 3406 ENGINE

Time to 10% Opacity in Minutes

| Starting Temp., °C | Fuel A | Fuel B | Fuel C | Fuel D | Fuel E | Fuel F |
|---|---|---|---|---|---|---|
| 20 | 0.1 | 0.2 | 2 | 0.3 | 0.8 | 0.3 |
| 0 | 1.9 | 4.3 | 7 | 4.5 | 6 | 3.3 |
| -15 | 6 | 10.5 | 13 | 9.5 | 11.3 | 7 |
| -25 | 8 | No Start | 15.5 | No Start | 15.5 | 9.8 |

TABLE 8

WARM-UP RATE OF CATERPILLAR 3406 ENGINE

(Started at -15°C; Engine Left Running at Idle)

| Idling Time (min) | Averaged Oil and Coolant Temperatures (°C) | | | | | |
|---|---|---|---|---|---|---|
| | Fuel A | Fuel B | Fuel C | Fuel D | Fuel E | Fuel F |
| 0 | -13.8 | -11.9 | -12.2 | -10.7 | -12.1 | -11.5 |
| 3 | -3.9 | -3.4 | -3.7 | -2.4 | -3.5 | -3.4 |
| 6 | 5.1 | 5.3 | 5.6 | 5.7 | 5.7 | 6.1 |
| 9 | 11.8 | 11.9 | 11.6 | 12.7 | 12.6 | 13.2 |
| 12 | 17.9 | 17.8 | 17.4 | 18.6 | 18.2 | 19.4 |
| 15 | 23.5 | 23.0 | 21.8 | 22.9 | 22.8 | 24.3 |
| Temp. Increase After 15 Minutes | 37.3 | 34.9 | 34.0 | 34.6 | 34.9 | 35.8 |

TABLE 9

IGNITION DELAY (MS) AFTER STARTING AT 20°C

| Idling Time (min) | Fuel A | Fuel B | Fuel C | Fuel D | Fuel E | Fuel F |
|---|---|---|---|---|---|---|
| 0 | 3.40 | 4.58 | 4.88 | 4.50 | 4.52 | 4.62 |
| 3 | 3.24 | 3.74 | 4.14 | 3.96 | 3.86 | 3.42 |
| 6 | 3.12 | 3.68 | 3.80 | 3.62 | 3.74 | 3.58 |
| 9 | 2.98 | 3.56 | 3.80 | 3.64 | 3.50 | 3.42 |
| 12 | 3.00 | 3.44 | 3.64 | 3.40 | 3.28 | 3.24 |
| 15 | 2.98 | 3.46 | 3.38 | 3.38 | 3.26 | 3.10 |

TABLE 10

IGNITION DELAY (MS) AFTER STARTING AT 0°C

| Idling Time (min) | Fuel A | Fuel B | Fuel C | Fuel D | Fuel E | Fuel F |
|---|---|---|---|---|---|---|
| 0 | -<br>6.38 | 4.18<br>4.34 | 4.82 | 4.14 | 5.12 | 4.92 |
| 3 | 7.68<br>4.10 | 4.18<br>4.52 | 4.26 | 4.18 | 4.92 | 4.24 |
| 6 | 3.86<br>3.70 | 4.16<br>4.40 | 4.02 | 4.02 | 4.24 | 3.90 |
| 9 | 3.52<br>3.34 | 3.94<br>3.96 | 3.94 | 3.76 | 3.90 | 3.60 |
| 12 | 3.18<br>3.18 | 3.60<br>3.66 | 3.50 | 3.66 | 3.68 | 3.42 |
| 15 | 3.12<br>3.24 | 3.56<br>3.38 | 3.44 | 3.60 | 3.56 | 3.18 |

* Note: Single determination for Fuels C, D, E and F.

TABLE 11

IGNITION DELAY (MS) AFTER STARTING AT -15°C

| Idling Time (min) | Fuel A | Fuel B | Fuel C | Fuel D | Fuel E | Fuel F |
|---|---|---|---|---|---|---|
| 0 | MF | MF | MF | MF | MF | MF |
| 3 | 6.70 | MF | MF | MF | MF | MF |
| 6 | 4.94 | MF | MF | MF | MF | 4.66 |
| 9 | 4.10 | MF | MF | MF | MF | 4.22 |
| 12 | 3.84 | 4.38 | 4.50 | 4.24 | 4.34 | 3.96 |
| 15 | 3.54 | 4.02 | 4.14 | 4.10 | 4.04 | 3.66 |

* Note: MF = Misfire.

TABLE 12

IGNITION DELAY DATA FOR CATERPILLAR 3406 ENGINE (MILLISECONDS)

Oil Temperature = 92°C; Coolant Temperature = 85°C

| RPM | Torque (N-m) | Fuel A | Fuel B | Fuel C | Fuel D | Fuel E | Fuel F |
|---|---|---|---|---|---|---|---|
| 1200 | 775 | 1.31 | 1.40 | 1.35 | 1.36 | 1.29 | 1.25 |
| | | 1.10 | 1.28 | 1.36 | 1.24 | 1.32 | 1.26 |
| | | (1.21) | (1.34) | (1.36) | (1.30) | (1.31) | (1.26) |
| 1200 | 1484-1580 | 0.99 | 0.77 | 0.81 | 0.84 | 0.71 | 0.57 |
| | | 0.80 | 0.90 | 0.97 | 0.69 | 0.72 | 0.75 |
| | | (0.89) | (0.84) | (0.89) | (0.77) | (0.72) | (0.66) |
| 1600 | 475 | 1.05 | 1.20 | 1.24 | 1.16 | 1.23 | 1.11 |
| | | 1.06 | 1.25 | 1.27 | 1.13 | 1.21 | 1.08 |
| | | (1.06) | (1.23) | (1.26) | (1.15) | (1.22) | (1.10) |
| 1600 | 1315-1414 | 0.55 | 0.56 | 0.61 | 0.64 | 0.62 | 0.61 |
| | | 0.61 | 0.57 | 0.59 | 0.61 | 0.65 | 0.54 |
| | | (0.58) | (0.57) | (0.60) | (0.63) | (0.64) | (0.58) |
| 1800 | 630 | 0.70 | 0.83 | 0.88 | 0.83 | 0.82 | 0.75 |
| | | 0.74 | 0.87 | 0.83 | 0.78 | 0.83 | 0.81 |
| | | (0.72) | (0.85) | (0.86) | (0.81) | (0.83) | (0.78) |
| 1800 | 1190-1302 | 0.46 | 0.47 | 0.55 | 0.54 | 0.49 | 0.43 |
| | | 0.41 | 0.54 | 0.58 | 0.56 | 0.55 | 0.55 |
| | | (0.44) | (0.51) | (0.57) | (0.55) | (0.52) | (0.49) |

Note: ( ) represents averaged values.

TABLE 13

CYLINDER PRESSURE RISE (kPa/CA°) FOR CAT 3406 ENGINE

| RPM | Torque (N-m) | Fuel A | Fuel B | Fuel C | Fuel D | Fuel E | Fuel F |
|---|---|---|---|---|---|---|---|
| 1200 | 775 | 317 | 407 | 393 | 373 | 380 | 352 |
| | | 338 | 380 | 428 | 373 | 414 | 359 |
| | | (328) | (394) | (411) | (373) | (397) | (356) |
| 1200 | 1484-1580 | 393 | 386 | 414 | 393 | 407 | 380 |
| | | 380 | 366 | 400 | 386 | 407 | 386 |
| | | (387) | (376) | (407) | (390) | (407) | (383) |
| 1600 | 475 | 345 | 428 | 380 | 345 | 380 | 373 |
| | | 366 | 393 | 462 | 373 | 462 | 345 |
| | | (356) | (411) | (421) | (359) | (421) | (359) |
| 1600 | 1315-1414 | 331 | 352 | 359 | 331 | 359 | 345 |
| | | 331 | 331 | 366 | 338 | 442 | 331 |
| | | (331) | (345) | (363) | (335) | (401) | (338) |
| 1800 | 630 | 311 | 338 | 359 | 352 | 338 | 331 |
| | | 297 | 352 | 373 | 338 | 359 | 311 |
| | | (304) | (345) | (366) | (345) | (349) | (321) |
| 1800 | 1190-1302 | 345 | 345 | 373 | 366 | 366 | 359 |
| | | 359 | 373 | 366 | 338 | 366 | 366 |
| | | (352) | (359) | (370) | (352) | (366) | (363) |

TABLE 14

EFFECTS OF FUEL PROPERTIES ON CYLINDER PRESSURE RISE

| Fuel Effects | Averaged Cylinder Pressure Rise (kPa/CA°)* of the Fuels Under Comparison | Comment |
|---|---|---|
| Decreased Cetane | A versus B; 329 versus 383 | Increased |
| Increased $T_{90}$ | B versus C; 383 versus 399 | Increased Slightly |
| Use of Cetane Improver | B versus F; 383 versus 345 | Decreased |
| Natural versus Ignition-Improved Cetane | B versus D; 383 versus 359 | The decrease could be due to higher cetane for D relative to B (38 versus 36) |
| Conventional versus Synthetic Fuels | C versus E; 399 versus 389 | No Effect |

Note: Average of the cylinder pressure rise of a given fuel under the three intermediate torque conditions.

TABLE 15

PEAK CYLINDER PRESSURE (BAR) FOR THE CATERPILLAR 3406 ENGINE

| RPM | Torque (N-m) | Fuel A | Fuel B | Fuel C | Fuel D | Fuel E | Fuel F |
|---|---|---|---|---|---|---|---|
| 1200 | 775 | 87.2 | 85.5 | 85.7 | 85.8 | 85.6 | 86.0 |
| | | 86.8 | 84.6 | 86.3 | 86.3 | 88.2 | 85.6 |
| | | (87.0) | (85.1) | (86.0) | (86.1) | (86.9) | (85.8) |
| 1200 | 1484-1580 | 121.1 | 121.2 | 125.1 | 123.3 | 125.9 | 121.2 |
| | | 119.3 | 119.1 | 125.7 | 121.0 | 125.8 | 121.9 |
| | | (120.2) | (120.2) | (125.4) | (122.2) | (125.9) | 121.6 |
| 1600 | 475 | 75.1 | 75.2 | 76.9 | 73.8 | 76.8 | 73.5 |
| | | 75.7 | 75.1 | 76.9 | 76.3 | 76.6 | 75.1 |
| | | (75.4) | (75.2) | (76.9) | (75.1) | (76.7) | (74.3) |
| 1600 | 1315-1414 | 119.3 | 119.8 | 124.9 | 120.4 | 125.5 | 121.6 |
| | | 118.7 | 119.1 | 125.8 | 122.2 | 124.2 | 119.8 |
| | | (119.0) | (119.5) | (125.4) | (121.3) | (124.9) | (120.7) |
| 1800 | 630 | 88.8 | 89.0 | 91.1 | 89.3 | 90.0 | 88.7 |
| | | 88.5 | 89.6 | 91.1 | 92.5 | 90.5 | 89.0 |
| | | (88.7) | (89.3) | (91.1) | (90.9) | (90.3) | (88.9) |
| 1800 | 1190-1302 | 120.6 | 122.0 | 126.2 | 123.0 | 125.1 | 121.9 |
| | | 119.7 | 122.2 | 128.8 | 123.1 | 125.1 | 122.2 |
| | | (120.2) | (122.1) | (127.5) | (123.1) | (125.1) | (122.1) |

Note: ( ) represents averaged values.

TABLE 16

MAXIMUM TORQUE (N-m) FOR CATERPILLAR 3406 ENGINE

| RPM | Fuel A | Fuel B | Fuel C | Fuel D | Fuel E | Fuel F |
|---|---|---|---|---|---|---|
| 1200 | 1495 | 1520 | 1573 | 1513 | 1570 | 1522 |
| | 1484 | 1520 | 1579 | 1520 | 1565 | 1520 |
| | (1490) | (1520) | 1580 | (1517) | (1568) | (1521) |
| | | | (1577) | | | |
| 1600 | 1330 | 1343 | 1403 | 1350 | 1395 | 1352 |
| | 1315 | 1340 | 1414 | 1355 | 1400 | 1350 |
| | (1323) | (1342) | 1405 | (1353) | (1398) | (1351) |
| | | | (1407) | | | |
| 1800 | 1195 | 1230 | 1274 | 1240 | 1285 | 1230 |
| | 1190 | 1225 | 1302 | 1250 | 1265 | 1224 |
| | (1193) | (1228) | 1284 | (1245) | (1275) | (1227) |
| | | | (1287) | | | |

Note: ( ) represents averaged values.

TABLE 17

BLACK SMOKE PRODUCTION FROM CATERPILLAR 3406 ENGINE (% OPACITY)

| RPM | Torque (N-m) | Fuel A | Fuel B | Fuel C | Fuel D | Fuel E | Fuel F |
|---|---|---|---|---|---|---|---|
| 1200 | 775 | 2.5 | 1.1 | 1.3 | 1.6 | 1.6 | 1.4 |
| | | 1.5 | 2.3 | 2.5 | 2.3 | 1.4 | 1.5 |
| | | (2.0) | (1.7) | (1.9) | (2.0) | (1.5) | (1.5) |
| 1200 | 1484-1580 | 5.3 | 4.0 | 4.2 | 4.5 | 4.3 | 5.0 |
| | | 4.2 | 5.0 | 5.3 | 4.9 | 4.1 | 4.3 |
| | | (4.6) | (4.5) | (4.6) | (4.7) | (4.2) | (4.7) |
| 1600 | 475 | 2.9 | 1.0 | 0.8 | 0.9 | 1.7 | 1.2 |
| | | 1.3 | 1.4 | 1.9 | 1.7 | 1.4 | 1.1 |
| | | (2.1) | (1.2) | (1.4) | (1.3) | (1.6) | (1.2) |
| 1600 | 1315-1414 | 5.2 | 3.9 | 3.5 | 4.0 | 4.3 | 4.4 |
| | | 4.1 | 4.3 | 4.4 | 4.4 | 4.4 | 4.6 |
| | | (4.7) | (4.1) | (4.0) | (4.2) | (4.4) | (4.5) |
| 1800 | 630 | 3.2 | 1.4 | 0.8 | 1.4 | 2.0 | 1.6 |
| | | 1.8 | 1.5 | 1.4 | 1.9 | 1.3 | 2.0 |
| | | (2.5) | (1.5) | (1.1) | (1.7) | (1.7) | (1.8) |
| 1800 | 1190-1302 | 4.3 | 3.5 | 3.1 | 3.1 | 3.6 | 3.4 |
| | | 3.5 | 3.2 | 3.5 | 3.7 | 2.9 | 4.1 |
| | | (3.9) | (3.4) | (3.3) | (3.4) | (3.3) | (3.8) |

Note: ( ) represents averaged values.

TABLE 18

HYDROCARBON EMISSIONS (PPM) FROM CATERPILLAR 3406 ENGINE

| RPM | Torque (N-m) | Fuel A | Fuel B | Fuel C | Fuel D | Fuel E | Fuel F |
|---|---|---|---|---|---|---|---|
| 1200 | 775 | 145 | 155 | 111 | 137 | 133 | 124 |
| | | 148 | 148 | 108 | 118 | 115 | 140 |
| | | (147) | (152) | (110) | (128) | (124) | (132) |
| 1200 | 1484-1580 | 51 | 63 | 88 | 60 | 58 | 65 |
| | | 65 | 59 | 86 | 61 | 56 | 70 |
| | | (58) | (61) | (87) | (61) | (57) | (68) |
| 1600 | 475 | 125 | 127 | 105 | 128 | 116 | 122 |
| | | 130 | 122 | 109 | 125 | 106 | 128 |
| | | (128) | (125) | (107) | (127) | (111) | (125) |
| 1600 | 1315-1414 | 69 | 90 | 53 | 76 | 61 | 74 |
| | | 73 | 83 | 53 | 74 | 58 | 82 |
| | | (71) | (87) | (53) | (75) | (60) | (78) |
| 1800 | 630 | 103 | 104 | 73 | 104 | 86 | 105 |
| | | 142 | 99 | 79 | 106 | 86 | 111 |
| | | (123) | (103) | (76) | (105) | (86) | (108) |
| 1800 | 1190-1302 | 69 | 78 | 54 | 57 | 64 | 80 |
| | | 77 | 73 | 56 | 76 | 63 | 76 |
| | | (73) | (76) | (55) | (67) | (64) | (78) |

Note: ( ) represents averaged values.

TABLE 19

FUEL EFFECTS ON HYDROCARBON EMISSIONS

| Fuel Effects | Averaged HC Emissions (ppm) of the Fuels Under Comparion* | Comment |
|---|---|---|
| Decreased Cetane | A versus B; 100 versus 100 | No Effect |
| Increased $T_{90}$ | B versus C; 100 versus 81 | Decreased |
| Use of Cetane Improver | B versus F; 100 versus 98 | No Effect |
| Natural versus Ignition-Improved Cetane | B versus D; 100 versus 94 | No Effect |
| Conventional versus Synthetic Fuels | C versus E; 81 versus 84 | No Effect |

* Note: Average of the HC production from a given fuel under the six test conditions.

TABLE 20

AVERAGED EXHAUST TEMPERATURE (°C) FROM CATERPILLAR 3406 ENGINE

| RPM | Torque (N-m) | Fuel A | Fuel B | Fuel C | Fuel D | Fuel E | Fuel F |
|---|---|---|---|---|---|---|---|
| 1200 | 775 | 448 | 451 | 447 | 449 | 448 | 447 |
| 1200 | 1484-1580 | 595 | 597 | 601 | 597 | 603 | 601 |
| 1600 | 475 | 344 | 346 | 344 | 345 | 345 | 344 |
| 1600 | 1315-1414 | 499 | 501 | 503 | 500 | 507 | 504 |
| 1800 | 630 | 384 | 384 | 381 | 385 | 385 | 385 |
| 1800 | 1190-1302 | 465 | 468 | 469 | 468 | 472 | 470 |

TABLE 21

CARBON MONOXIDE EMISSIONS (PPM) FROM CATERPILLAR 3406 ENGINE

| RPM | Torque (N-m) | Fuel A | Fuel B | Fuel C | Fuel D | Fuel E | Fuel F |
|---|---|---|---|---|---|---|---|
| 1200 | 775 | 220 | 230 | 280 | 260 | 230 | 190 |
| | | 210 | 270 | 240 | 215 | 217 | 230 |
| | | (215) | (250) | (260) | (238) | (224) | (210) |
| 1200 | 1484-1580 | 725 | 640 | 900 | 775 | 730 | 615 |
| | | 655 | 750 | 710 | 680 | 707 | 715 |
| | | (690) | (695) | (805) | (723) | (719) | (665) |
| 1600 | 475 | 215 | 235 | 285 | 260 | 255 | 210 |
| | | 220 | 245 | 265 | 230 | 237 | 230 |
| | | (218) | (240) | (275) | (245) | (246) | (220) |
| 1600 | 1315-1414 | 315 | 275 | 330 | 310 | 315 | 270 |
| | | 290 | 290 | 290 | 280 | 297 | 298 |
| | | (303) | (283) | (310) | (295) | (306) | (284) |
| 1800 | 630 | 180 | 175 | 205 | 195 | 190 | 170 |
| | | 170 | 175 | 190 | 180 | 180 | 175 |
| | | (175) | (175) | (198) | (188) | (185) | (173) |
| 1800 | 1190-1302 | 212 | 185 | 220 | 205 | 210 | 185 |
| | | 200 | 205 | 200 | 190 | 190 | 205 |
| | | (206) | (195) | (210) | (198) | (200) | (195) |

Note: ( ) represents averaged values.

TABLE 22

FUEL EFFECTS ON CARBON MONOXIDE EMISSIONS

| Fuel Effects | Averaged CO Emissions (ppm) of the Fuels Under Comparion* | Comment |
|---|---|---|
| Decreased Cetane | A versus B; 301 versus 306 | No Effect |
| Increased $T_{90}$ | B versus C; 306 versus 343 | Increased |
| Use of Cetane Improver | B versus F; 306 versus 291 | No Effect |
| Natural versus Ignition-Improved Cetane | B versus D; 306 versus 315 | No Effect |
| Conventional versus Synthetic Fuels | C versus E; 343 versus 313 | Synthetic fuel apparently produced less CO which could be due to higher back-end volatility |

* Note: Average of the CO production from a given fuel under the six test conditions.

TABLE 23

NITROGEN OXIDE EMISSIONS FROM CATERPILLAR 3406 ENGINE

| RPM | Torque (N-m) | Fuel A | Fuel B | Fuel C | Fuel D | Fuel E | Fuel F |
|---|---|---|---|---|---|---|---|
| 1200 | 775 | 958 | 1008 | 1035 | 928 | 965 | 1048 |
| | | 950 | 1018 | 1028 | 1053 | 1045 | 930 |
| | | (954) | (1013) | (1032) | (991) | (1005) | (989) |
| 1200 | 1484-1580 | 983 | 1078 | 900 | 1023 | 995 | 1083 |
| | | 955 | 1120 | 1213 | 1075 | 1080 | 923 |
| | | (969) | (1099) | (1057) | (1049) | (1038) | (1003) |
| 1600 | 475 | 613 | 655 | 670 | 615 | 603 | 683 |
| | | 690 | 660 | 693 | 653 | 653 | 570 |
| | | (652) | (658) | (682) | (634) | (628) | (627) |
| 1600 | 1315-1414 | 813 | 868 | 935 | 808 | 863 | 903 |
| | | 962 | 928 | 978 | 903 | 900 | 775 |
| | | (888) | (948) | (952) | (852) | (882) | (839) |
| 1800 | 630 | 780 | 803 | 808 | 733 | 770 | 818 |
| | | 765 | 818 | 860 | 788 | 778 | 745 |
| | | (773) | (811) | (834) | (761) | (774) | (782) |
| 1800 | 1190-1302 | 843 | 920 | 925 | 838 | 840 | 895 |
| | | 838 | 940 | 1013 | 913 | 928 | 813 |
| | | (841) | (930) | (969) | (876) | (884) | (854) |

Note: ( ) represents averaged values.

TABLE 24

FUEL EFFECTS ON NITROGEN OXIDE EMISSIONS

| Fuel Effects | Averaged $NO_x$ Emissions (ppm) of the Fuels Under Comparison* | Comment |
|---|---|---|
| Decreased Cetane | A versus B; 846 versus 910 | Increased |
| Increased $T_{90}$ | B versus C; 910 versus 910 | No Effect |
| Use of Cetane Improver | B versus F; 910 versus 849 | Decreased |
| Natural versus Ignition-Improved Cetane | B versus D; 910 versus 861 | Decreased (could be due to relatively higher cetane number) |
| Conventional versus Synthetic Fuels | C versus E; 921 versus 869 | Synthetic fuel produced less $NO_x$ |

* Note: Average of the $NO_x$ production from a given fuel under the six different test conditions.

TABLE 25

FUEL CONSUMPTION (G/MIN)

| RPM | Torque (N-m) | Fuel A | Fuel B | Fuel C | Fuel D | Fuel E | Fuel F |
|---|---|---|---|---|---|---|---|
| 1200 | 775 | 310.5 | 317.4 | 316.7 | 318.4 | 317.6 | 312.5 |
| | | 311.6 | 316.7 | 318.7 | 314.1 | 314.7 | 314.3 |
| | | (311.1) | 325.9 | 318.6 | 315.5 | (316.2) | 313.5 |
| | | | (320.0) | (318.0) | (316.0) | | (313.4) |
| 1200 | Max 1484-1580 | 612.8 | 627.9 | 656.6 | 632.4 | 653.7 | 635.1 |
| | | 612.1 | 632.9 | 659.1 | 633.3 | 650.0 | 633.3 |
| | | (612.5) | 630.1 | 660.1 | 634.5 | (651.9) | 633.6 |
| | | | (630.3) | (658.6) | (633.4) | | (634.0) |
| 1600 | 475 | 275.7 | 282.0 | 285.9 | 281.9 | 283.6 | 279.1 |
| | | 277.4 | 282.2 | 286.2 | 282.9 | 282.0 | 281.7 |
| | | (276.6) | 284.8 | 285.0 | 281.9 | (282.8) | 276.3 |
| | | | (283.0) | (285.7) | (282.2) | | (279.0) |
| 1600 | Max 1315-1414 | 728.7 | 751.0 | 783.1 | 751.3 | 773.7 | 752.8 |
| | | 724.8 | 748.1 | 780.1 | 753.0 | 772.2 | 752.0 |
| | | (726.8) | 748.9 | 783.4 | 755.0 | (773.0) | 749.1 |
| | | | (749.3) | (782.2) | (753.1) | | (751.3) |
| 1800 | 630 | 405.8 | 422.3 | 421.9 | 424.4 | 427.8 | 414.0 |
| | | 415.7 | 418.6 | 422.0 | 423.3 | 418.8 | 423.4 |
| | | (410.8) | 422.6 | 420.3 | 433.3 | (423.3) | 417.3 |
| | | | (421.2) | (421.4) | (427.0) | | (418.2) |
| 1800 | Max 1190-1302 | 746.8 | 779.7 | 822.8 | 787.1 | 810.2 | 779.1 |
| | | 746.1 | 778.7 | 807.3 | 788.5 | 797.4 | 777.3 |
| | | (746.5) | 781.0 | 813.0 | 792.3 | (803.8) | 775.8 |
| | | | (779.8) | (814.4) | (789.3) | | (777.4) |

Note: ( ) represents averaged values.

TABLE 26

SPECIFIC FUEL CONSUMPTION (g/kW-hr) FOR CATERPILLAR 3406 ENGINE

| RPM | Torque (N-m) | Fuel A | Fuel B | Fuel C | Fuel D | Fuel E | Fuel F |
|---|---|---|---|---|---|---|---|
| 1200 | 775 | 191.7 | 197.2 | 195.9 | 194.7 | 194.8 | 193.1 |
| 1200 | 1484-1580 | 196.3 | 198.0 | 199.4 | 199.4 | 198.5 | 199.0 |
| 1600 | 475 | 208.5 | 213.4 | 215.4 | 212.8 | 213.2 | 210.4 |
| 1600 | 1315-1414 | 196.7 | 200.0 | 199.1 | 199.3 | 198.0 | 199.2 |
| 1800 | 630 | 207.6 | 212.8 | 212.9 | 215.8 | 213.9 | 211.3 |
| 1800 | 1190-1302 | 199.2 | 202.1 | 201.4 | 201.8 | 200.7 | 201.7 |

Note: Specific Fuel Consumption (g/kW-hr)

$$= \frac{\text{Fuel Consumption (g/min)} \times 60 \times 9550}{\text{Torque (N-m)} \times \text{RPM}}$$

TABLE 27

FUEL EFFECTS ON SPECIFIC FUEL CONSUMPTION

| Fuel Effects | Averaged Specific Fuel Consumption (g/kW-hr) of the Fuels Under Comparison* | Comment |
|---|---|---|
| Decreased Cetane | A versus B; 200 versus 204 | Increased |
| Increased $T_{90}$ | B versus C; 204 versus 204 | No Effect |
| Use of Cetane Improver | B versus F; 204 versus 202 | Slightly Reduced |
| Natural versus Ignition-Improved Cetane | B versus D; 204 versus 204 | No Effect |
| Conventional versus Synthetic Fuels | C versus E; 204 versus 203 | No Effect |

* Note: Average of the specific fuel consumption for a given fuel under the six different test conditions.

TABLE 28

FUEL CONSUMPTION (L/kW-hr) FOR CATERPILLAR 3406 ENGINE

| RPM | Torque (N-m) | Fuel A | Fuel B | Fuel C | Fuel D | Fuel E | Fuel F |
|---|---|---|---|---|---|---|---|
| 1200 | 775 | 0.226 | 0.229 | 0.226 | 0.226 | 0.224 | 0.224 |
| 1200 | 1484-1580 | 0.232 | 0.230 | 0.226 | 0.231 | 0.228 | 0.231 |
| 1600 | 475 | 0.246 | 0.248 | 0.245 | 0.246 | 0.245 | 0.244 |
| 1600 | 1315-1414 | 0.232 | 0.232 | 0.226 | 0.231 | 0.227 | 0.231 |
| 1800 | 630 | 0.245 | 0.247 | 0.242 | 0.250 | 0.245 | 0.245 |
| 1800 | 1190-1302 | 0.235 | 0.235 | 0.229 | 0.234 | 0.230 | 0.234 |

TABLE 29

FUEL EFFECTS ON VOLUMETRIC FUEL CONSUMPTION

| | Fuel A | Fuel B | Fuel C | Fuel D | Fuel E | Fuel F |
|---|---|---|---|---|---|---|
| Averaged Fuel Consumption in L/kW-hr under the Six Test Sonditions | 0.236 | 0.237 | 0.232 | 0.236 | 0.233 | 0.235 |
| Cetane Number | 42.5 | 36.3 | 35.8 | 38.1 | 35.6 | 41.0 |
| Density at 15°C, kg/L | 0.8465 | 0.8612 | 0.8804 | 0.8633 | 0.8715 | 0.8615 |

TABLE 30

THE EFFECT OF INDIVIDUAL FUEL QUALITY PARAMETERS ON TRUCK COLD STARTING AT -25°C

| Fuel Quality Parameter | Truck Engine | Total Cranking Time to Startup at -25°C (seconds) | |
|---|---|---|---|
| Natural Cetane | | Fuel A | Fuel B |
| | Caterpillar 3406 | 1 | 8 |
| | Cummins NTC-400 | 2 | 3 |
| | Mack E6-350 | 2 | 1 |
| | Detroit Diesel 8V92 | 95 (H, E)(1) | 139 (H, 2E)(1) |
| Natural versus Ignition-Improved Cetane | | Fuel B | Fuel D |
| | Caterpillar 3406 | 8 | 7 |
| | Cummins NTC-400 | 3 | 1 |
| | Mack E6-350 | 1 | 1 |
| | Detroit Diesel 8V92 | 139 (H, 2E)(1) | 75 (H, 3E)(1) |
| | | Fuel A | Fuel F |
| | Caterpillar 3406 | 1 | 22 |
| | Cummins NTC-400 | 2 | 2 |
| | Mack E6-350 | 2 | 1 |
| | Detroit Diesel 8V92 | 95 (H, E)(1) | 134 (H, 2E)(1) |
| Ignition Improver | | Fuel B | Fuel F |
| | Caterpillar 3406 | 8 | 22 |
| | Cummins NTC-400 | 3 | 2 |
| | Mack E6-350 | 1 | 1 |
| | Detroit Diesel 8V92 | 139 (H, 2E)(1) | 134 (H, 2E)(1) |
| Back-End Volatility (90% Point) | | Fuel B | Fuel C |
| | Caterpillar 3406 | 8 | 63 (H)(1) |
| | Cummins NTC-400 | 3 | 15 |
| | Mack E6-350 | 1 | 3 |
| | Detroit Diesel 8V92 | 139 (H, 2E)(1) | 100 (H, 2E)(1) |
| Conventional versus Synthetic Crude Source | | Fuel C | Fuel E |
| | Caterpillar 3406 | 63 (H)(1) | 4 |
| | Cummins NTC-400 | 15 | 105 (H)(1) |
| | Mack E6-350 | 3 | 3 |
| | Detroit Diesel 8V92 | 100 (H, 2E)(1) | 128 (H, 2E)(1) |

(1) H = Hot Battery used.
nE = Number of attempts using ether injection.

TABLE 31

A COMPARISON OF ENGINE TEMPERATURES AND
COLD STARTING PERFORMANCE FOR THE TEST TRUCKS ON FUEL E

| Truck Engine | Soak Temperature (°C) | Coolant Temperature (°C) | Sump Oil Temperature (°C) | Total Cranking Time for Fuel E (seconds) |
|---|---|---|---|---|
| Caterpillar 3406 | 0 | 41 | 22 | 1 |
| | -15 | 28 | 7 | 1 |
| | -25 | 24 | -1 | 4 |
| | -30 | 20 | -9 | 16 |
| Mack E6-350 | 0 | 56 | 13 | 1 |
| | -15 | 40 | 10 | 1 |
| | -25 | 37 | 1 | 3 |
| | -30 | 29 | -16 | 2 |
| Cummins NTC-400 | 0 | 52 | 24 | 1 |
| | -15 | 42 | 12 | 1 |
| | -25 | 30 | 0 | 105 (H)(1) |
| | -30 | 30 | -2 | 116 (H, E)(1) |
| Detroit Diesel 8V92 | 0 | 36 | 22 | 1 |
| | -15 | 22 | 9 | 38 |
| | -25 | 15 | 0 | 128 (H, 2E) |

(1) H = Hot Battery used.
nE = Number of attempts using ether injection.

TABLE 32

THE EFFECT OF INDIVIDUAL FUEL QUALITY PARAMETERS ON IDLE WHITE SMOKE INTENSITY AT -25°C

| Fuel Quality Parameter | Truck Engine | Time to 10% Exhaust Smoke Opacity at -25°C (minutes)(1) | |
|---|---|---|---|
| Natural Cetane | | Fuel A | Fuel B |
| | Caterpillar 3406 | 13.8 | 15+ (29%) |
| | Cummins NTC-400 | 15+ (16%) | 15+ (66%) |
| | Mack E6-350 | 2.2 | 15+ (16%) |
| | Detroit Diesel 8V92 | <1 | 6.1 |
| Natural versus Ignition-Improved Cetane | | Fuel B | Fuel D |
| | Caterpillar 3406 | 15+ (29%) | 15+ (23%) |
| | Cummins NTC-400 | 15+ (66%) | 15+ (26%) |
| | Mack E6-350 | 15+ (16%) | 15+ (22%) |
| | Detroit Diesel 8V92 | 6.1 | 9.3 |
| | | Fuel A | Fuel F |
| | Caterpillar 3406 | 13.8 | 15+ (30%) |
| | Cummins NTC-400 | 15+ (16%) | 15+ (21%) |
| | Mack E6-350 | 2.2 | 7.3 |
| | Detroit Diesel 8V92 | <1 | 2.8 |
| Ignition Improver | | Fuel B | Fuel F |
| | Caterpillar 3406 | 15+ (29%) | 15+ (30%) |
| | Cummins NTC-400 | 15+ (66%) | 15+ (21%) |
| | Mack E6-350 | 15+ (16%) | 7.3 |
| | Detroit Diesel 8V92 | 6.1 | 2.8 |
| Back-End Volatility (90% Point) | | Fuel B | Fuel C |
| | Caterpillar 3406 | 15+ (29%) | 15+ (71%) |
| | Cummins NTC-400 | 15+ (66%) | 15+ (71%) |
| | Mack E6-350 | 15+ (16%) | 15+ (36%) |
| | Detroit Diesel 8V92 | 6.1 | 8.8 |
| Conventional versus Synthetic Crude Source | | Fuel C | Fuel E |
| | Caterpillar 3406 | 15+ (71%) | 15+ (26%) |
| | Cummins NTC-400 | 15+ (71%) | 15+ (67%) |
| | Mack E6-350 | 15+ (36%) | 15+ (32%) |
| | Detroit Diesel 8V92 | 8.8 | 5.0 |

(1) % opacity at 15 minutes idling mark shown in parentheses, if opacity value is higher than 10%.

TABLE 33

THE EFFECT OF TEMPERATURE ON IDLE WHITE SMOKE INTENSITY FOR FUEL E

| Truck Engine | Soak Temperature (°C) | Time to 10% Exhaust Smoke Opacity for Fuel E (minutes)(1) |
|---|---|---|
| Caterpillar 3406 | 0 | 9.2 |
| | -15 | 15+ (19%) |
| | -25 | 15+ (26%) |
| | -30 | 15+ (44%) |
| Cummins NTC-400 | 0 | 12.1 |
| | -15 | 15+ (36%) |
| | -25 | 15+ (67%) |
| | -30 | 15+ (90%) |
| Mack E6-350 | 0 | <1 |
| | -15 | 4.3 |
| | -25 | 15+ (32%) |
| | -30 | 15+ (93%) |
| Detroit Diesel 8V92 | 0 | <1 |
| | -15 | 2.9 |
| | -25 | 5.0 |

(1) % opacity at 15 minutes idling mark shown in parentheses, if opacity value is higher than 10%.

TABLE 34

THE EFFECT OF ENGINE DESIGN ON IDLE WHITE SMOKE INTENSITY AT -25°C

| Test Fuel | Time to 10% Exhaust Smoke Opacity (minutes)(1) | | | |
|---|---|---|---|---|
| | Caterpillar 3406 | Cummins NTC-400 | Mack E6-350 | Detroit Diesel 8V92 |
| A | 13.8 | 15+ (16%) | 2.2 | <1 |
| B | 15+ (29%) | 15+ (66%) | 15+ (16%) | 6.1 |
| C | 15+ (71%) | 15+ (71%) | 15+ (36%) | 8.8 |
| D | 15+ (23%) | 15+ (26%) | 15+ (22%) | 9.3 |
| E | 15+ (26%) | 15+ (67%) | 15+ (32%) | 5.0 |
| F | 15+ (30%) | 15+ (21%) | 7.3 | 2.8 |

(1) % opacity at 15 minutes idling mark shown in parentheses, if opacity value is higher than 10%.

TABLE 35

SUMMARY OF FUEL, TEMPERATURE AND ENGINE DESIGN EFFECTS ON DRIVEABILITY

| Truck Engine | Air Temperature (°C) | Fuel Code | Driveability Rating(1) | Driver's Comments |
|---|---|---|---|---|
| Caterpillar 3406 | 0 | A | Pass | Good run |
| | | B | Pass | Good run |
| | | C | Pass | Good run |
| | | D | Pass | Good run |
| | | E | Pass | Good run |
| | | F | Pass | Good run |
| | -15 | A | Pass | Good run |
| | | B | Pass | Good run |
| | | C | Pass | Good run |
| | | D | Pass | Good run |
| | | E | Pass | Good run |
| | | F | Pass | Good run |
| | -25 | A | Pass | Good run |
| | | B | Pass | Good run |
| | | C | Pass | Good run |
| | | D | Pass | Good run |
| | | E | Pass | Surging during first 3 minutes of idle |
| | | F | Pass | Good run |
| | -30 | E | Pass | Very rough idle initially |
| Cummins NTC-400 | 0 | A | Pass | Good run |
| | | B | Pass | Good run |
| | | D | Pass | Good run |
| | | D | Pass | Good run |
| | | E | Pass | Good run |
| | | F | Pass | Good run |
| | -15 | A | Pass | Good run |
| | | B | Pass | Good run |
| | | C | Pass | Good run |
| | | D | Pass | Good run |
| | | E | Pass | Good run |
| | | F | Pass | Good run |

(Cont'd) . . . . . .

TABLE 35 (CONT'D)

SUMMARY OF FUEL, TEMPERATURE AND ENGINE DESIGN EFFECTS ON DRIVEABILITY

| Truck Engine | Air Temperature (°C) | Fuel Code | Driveability Rating(1) | Driver's Comments |
|---|---|---|---|---|
| | -25 | A | Pass | Good run |
| | | B | Borderline Pass | Sluggish acceleration to 50 kph |
| | | C | Borderline Fail | No power for initial acceleration |
| | | D | Borderline Pass | Surging during initial acceleration |
| | | E | Borderline Fail | Prolonged idle and initial failure to hold 50 kph |
| | | F | Pass | Good run |
| | -30 | E | Fail | Very rough prolonged idle and no power to reach 50 kph |
| Mack E6-350 | 0 | A | Pass | Good run |
| | | B | Pass | Good run |
| | | C | Pass | Surging during final 10 minutes of idle |
| | | D | Pass | Good run |
| | | E | Pass | Good run |
| | | F | Pass | Good run |
| | -15 | A | Pass | Good run |
| | | B | Pass | Surging during final 10 minutes of idle |
| | | C | Pass | Good run |
| | | D | Pass | Good run |
| | | E | Pass | Good run |
| | | F | Pass | Good run |
| | -25 | A | Pass | Good run |
| | | B | Pass | Good run |
| | | C | Pass | Surging during final 8 minutes of idle |
| | | D | Pass | Good run |
| | | E | Pass | Good run |
| | | F | Pass | Good run |
| | -30 | E | Borderline Pass | Rough idle and initial hesitation in acceleration to 50 kph |

(Cont'd) . . . . . .

TABLE 35 (CONT'D)

SUMMARY OF FUEL, TEMPERATURE AND ENGINE DESIGN EFFECTS ON DRIVEABILITY

| Truck Engine | Air Temperature (°C) | Fuel Code | Driveability Rating(1) | Driver's Comments |
|---|---|---|---|---|
| Detroit Diesel 8V92 | 0 | A | Pass | Good run |
| | | B | Pass | Good run |
| | | C | Pass | Good run |
| | | D | Pass | Good run |
| | | E | Pass | Good run |
| | | F | Pass | Good run |
| | -15 | A | Pass | Dyno alarm interruption of 90 kph segment |
| | | B | Pass | Good run |
| | | C | Pass | Good run |
| | | D | Pass | Good run |
| | | E | Pass | Good run |
| | | F | Pass | Good run |
| | -25 | A | Pass | Good run |
| | | B | Pass | Good run |
| | | C | Pass | Severe idle roughness for first 12 minutes |
| | | D | Pass | Good run |
| | | E | Pass | Good run |
| | | F | Pass | Good run |

(1) Pass: Able to accelerate smoothly and maintain 50 and 90 kph speeds with no difficulty.
Borderline Pass: Able to complete run but acceleration sluggish.
Borderline Fail: Able to complete run but operational problems severe enough to cause customer complaints.
Fail: Unable to complete run.

TABLE 36

SUMMARY OF VOLUMETRIC FUEL CONSUMPTION DATA

| Truck Engine | Air Temperature (°C) | Fuel Code | Fuel Consumption (ℓ/100 km) 50 kph Mean(1) | 50 kph S.D. (%)(1) | 90 kph Mean(1) | 90 kph S.D. (%)(2) |
|---|---|---|---|---|---|---|
| Caterpillar 3406 | 0 | A | 38.02 | 1.14 | 46.54 | 0.86 |
| | | B | 43.76 | 1.65 | 49.94 | 1.04 |
| | | C | 38.01 | 0.85 | 46.21 | 0.40 |
| | | D | 39.59 | 0.04 | 46.09 | 0 |
| | | E | 37.41 | 1.80 | 46.01 | 1.08 |
| | | F | 38.47 | 1.32 | 47.23 | 0.96 |
| | -15 | A | 46.62 | 1.08 | 51.41 | 0.18 |
| | | B | 44.88 | 1.12 | 49.88 | 0.20 |
| | | C | 38.67 | 1.02 | 45.83 | 0.82 |
| | | D | 39.62 | 0.89 | 47.06 | 0.21 |
| | | E | 38.89 | 1.42 | 46.27 | 1.88 |
| | | F | 38.58 | 2.08 | 46.47 | 1.73 |
| | -25 | A | 40.78 | 2.64 | 47.76 | 0.19 |
| | | B | 40.31 | 2.51 | 47.80 | 1.31 |
| | | C | 38.46 | 1.94 | 46.66 | 0.50 |
| | | D | 40.30 | 1.77 | 47.36 | 0.45 |
| | | E | 39.70 | 1.82 | 46.29 | 2.28 |
| | | F | 40.59 | 2.20 | 46.77 | 0.49 |
| | -30 | E | 41.04 | 1.72 | 47.57 | 0.75 |
| Cummins NTC-400 | 0 | A | 36.72 | 0.91 | 44.54 | 1.01 |
| | | B | 36.88 | 0.60 | 44.19 | 0.28 |
| | | C | 36.80 | 1.33 | 43.34(3) | |
| | | D | 39.77 | 1.07 | 43.93 | 0.65 |
| | | E | 36.25 | 0.22 | 44.19 | 0.51 |
| | | F | 36.85 | 0.36 | 44.47 | 0.33 |
| | -15 | A | 41.83 | 0.34 | 45.79 | 0.04 |
| | | B | 38.10 | 0.26 | 45.62 | 0.23 |
| | | C | 36.85 | 0.02 | 44.64 | 0.47 |
| | | D | 38.40 | 0.58 | 45.31 | 0.18 |
| | | E | 41.45 | 2.27 | 44.87 | 0.43 |
| | | F | 37.21 | 0.13 | 45.39 | 0.81 |

(Cont'd) . . . . . .

TABLE 36 (CONT'D)

SUMMARY OF VOLUMETRIC FUEL CONSUMPTION DATA

| Truck Engine | Air Temperature (°C) | Fuel Code | Fuel Consumption (ℓ/100 km) 50 kph Mean(1) | 50 kph S.D. (%)(1) | 90 kph Mean(1) | 90 kph S.D. (%)(2) |
|---|---|---|---|---|---|---|
| | -25 | A | 39.02 | 2.70 | 45.93 | 1.66 |
| | | B | 37.94 | 1.45 | 45.59 | 0.02 |
| | | C | 39.82 | 7.44 | 45.60 | 0.56 |
| | | D | 38.21 | 1.86 | 45.90 | 0.41 |
| | | E | 38.27 | 1.14 | 45.74 | 0.02 |
| | | F | 39.04 | 1.37 | 46.09 | 0.45 |
| | -30 | E | ---------- unable to complete run ---------- | | | |
| Mack E6-350 | 0 | A | 42.38 | 0.97 | 45.52 | 1.84 |
| | | B | 33.77 | 0.63 | 43.69 | 1.05 |
| | | C | 32.98 | 1.36 | 43.43 | 0.35 |
| | | D | 34.13 | 0.41 | 40.76 | 0.26 |
| | | E | 33.52 | 1.33 | 40.60 | 0.32 |
| | | F | 35.72 | 1.38 | 40.11 | 1.45 |
| | -15 | A | 41.88 | 0.34 | 45.43 | 1.58 |
| | | B | 35.06 | 1.92 | 41.66 | 0.43 |
| | | C | 34.79 | 1.27 | 40.65 | 0.02 |
| | | D | 34.48 | 1.97 | 41.45 | 0.45 |
| | | E | 34.58 | 0.54 | 39.99 | 0.41 |
| | | F | 34.74 | 1.68 | 41.12 | 0.58 |
| | -25 | A | 42.26 | 1.19 | 45.83 | 0.16 |
| | | B | 36.26 | 1.95 | 41.60 | 0.28 |
| | | C | 35.69 | 1.37 | 41.42 | 0.43 |
| | | D | 35.68 | 2.39 | 41.24 | 0.73 |
| | | E | 34.87 | 0.58 | 40.24 | 0.14 |
| | | F | 36.30 | 2.24 | 41.61 | 0.73 |
| | -30 | E | 35.73 | 1.79 | 41.06 | 1.15 |
| Detroit Diesel 8V92 | 0 | A | 47.86 | 0.75 | 49.72 | 0.99 |
| | | B | 48.07 | 0.73 | 49.02 | 0.10 |
| | | C | 47.08 | 1.07 | 48.29 | 0.33 |
| | | D | 48.47 | 0.81 | 49.87 | 1.12 |
| | | E | 46.40 | 0.12 | 48.24 | 0.72 |
| | | F | 46.99 | 0.68 | 48.32 | 0.08 |

TABLE 36 (CONT'D)

SUMMARY OF VOLUMETRIC FUEL CONSUMPTION DATA

| Truck Engine | Air Temperature (°C) | Fuel Code | Fuel Consumption (ℓ/100 km) 50 kph Mean(1) | 50 kph S.D. (%)(1) | 90 kph Mean(1) | 90 kph S.D. (%)(2) |
|---|---|---|---|---|---|---|
| | -15 | A | 49.16 | 0.25 | 50.13 | 0.60 |
| | | B | 49.77 | 2.00 | 49.80 | 0.08 |
| | | C | 48.44 | 0.23 | 49.02 | 0.74 |
| | | D | 48.54 | 1.64 | 49.66 | 0.20 |
| | | E | 48.99 | 0.35 | 48.85 | 0.20 |
| | | F | 48.56 | 0.19 | 49.63 | 0.55 |
| | -25 | A | 52.98 | 0.96 | 50.16 | 1.65 |
| | | B | 50.69 | 0.83 | 51.02 | 0.87 |
| | | C | 49.23 | 1.42 | 49.48 | 1.15 |
| | | D | 49.90 | 1.23 | 49.90 | 0.94 |
| | | E | 49.44 | 1.71 | 49.19 | 0.99 |
| | | F | 49.41 | 1.53 | 50.28 | 0.07 |

(1) Mean of fuel consumption values for the second and third 5 minute segments of each constant speed section.
(2) Standard deviation.
(3) Single observation.

TABLE 37

COMPARISON OF TRUCK, TEMPERATURE AND FUEL EFFECTS ON FUEL CONSUMPTION

| Variable | Air Temperature (°C) | Fuel Code | Truck Engine | Fuel Consumption (ℓ/100 km) 50 kph | 90 kph |
|---|---|---|---|---|---|
| 1. Truck Engine | 0 | B | Caterpillar 3406 | 43.76 | 49.94 |
| | | | Cummins NTC-400 | 36.88 | 44.19 |
| | | | Mack E6-350 | 33.77 | 43.69 |
| | | | Detroit Diesel 8V92 | 48.07 | 49.72 |
| 2. Air Temperature | 0 | D | Cummins NTC-400 | 39.77 | 43.93 |
| | -15 | | | 38.40 | 45.31 |
| | -25 | | | 38.21 | 45.90 |
| | 0 | E | Detroit Diesel 8V92 | 46.40 | 48.24 |
| | -15 | | | 48.99 | 48.85 |
| | -25 | | | 49.44 | 49.19 |
| 3. Fuel | -15 | A | Cummins NTC-400 | 41.83 | 45.79 |
| | | B | | 38.10 | 45.62 |
| | | C | | 36.85 | 44.64 |
| | | D | | 38.40 | 45.31 |
| | | E | | 41.45 | 44.87 |
| | | F | | 37.21 | 45.39 |

TABLE 38

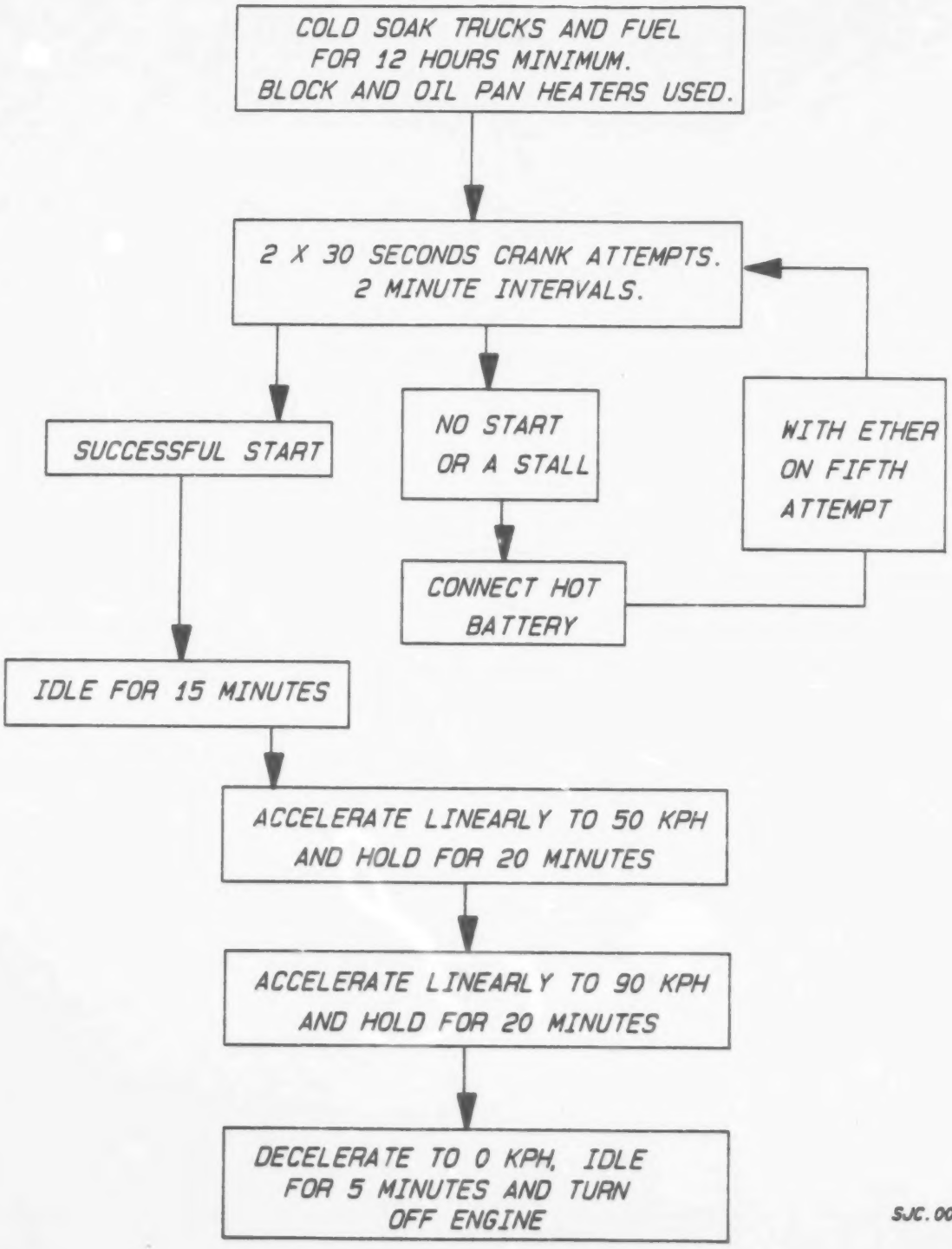
EFFECTS OF FUEL PROPERTIES ON PERFORMANCE

| Performance | Increase Cetane | Use of Cetane Improver | Natural versus Ignition Improved Cetane | Increase $T_{90}$ | Synthetic versus Conventional |
|---|---|---|---|---|---|
| Startability | Slightly Improved | Slightly Improved | No Effect | No Effect | No Effect |
| White Smoke Production | Decreased | Decreased | No Effect | Increased | No Effect |
| Ignition Delay (Warmed-Up Engine) | Decreased | Decreased | No Effect | No Effect | No Effect |
| Cylinder Pressure Rise | Decreased | Decreased | No Effect | Slightly Increased | No Effect |
| Black Smoke Production | No Effect | No Effect | No Effect | No Effect | No Effect |
| Hydrocarbon Emissions | No Effect | No Effect | No Effect | Decreased | No Effect |
| Carbon Monoxide Emissions | No Effect | No Effect | No Effect | Increased | No Effect |
| Nitrogen Oxide Emissions | Decreased | Decreased | No Effect | No Effect | Decreased |
| Specific Fuel Consumption (g/kW-hr) | Decreased | Slightly Decreased | No Effect | No Effect | No Effect |
| Fuel Economy (L/kW-hr) | No Effect | No Effect | No Effect | Decreased if Density was Increased | No Effect |

## 7. FIGURES

FIGURE 1

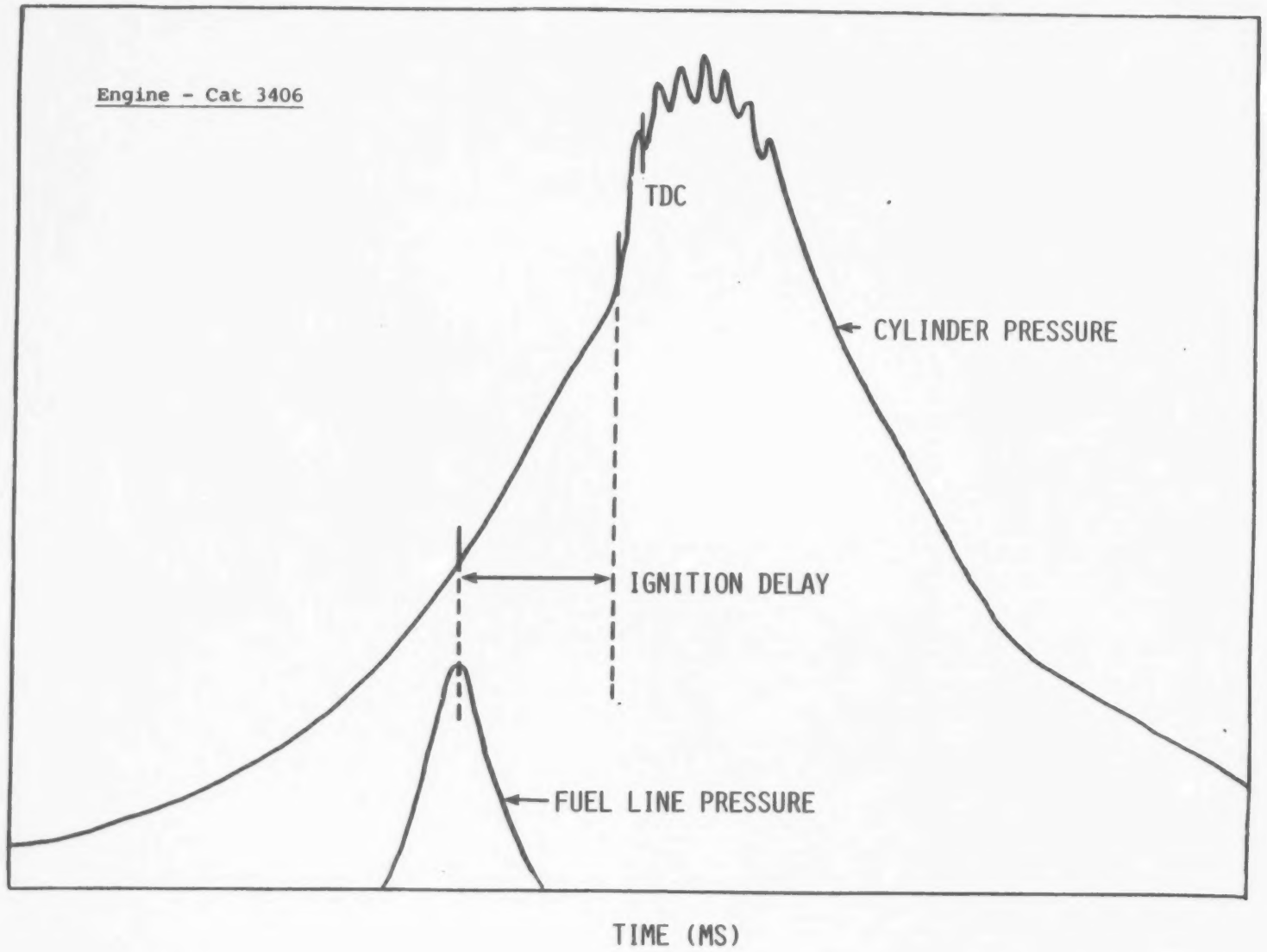
## COLD START AND DRIVE CYCLE PROCEDURE


COLD SOAK TRUCKS AND FUEL FOR 12 HOURS MINIMUM. BLOCK AND OIL PAN HEATERS USED.
2 X 30 SECONDS CRANK ATTEMPTS. 2 MINUTE INTERVALS.
SUCCESSFUL START
NO START OR A STALL
WITH ETHER ON FIFTH ATTEMPT
CONNECT HOT BATTERY
IDLE FOR 15 MINUTES
ACCELERATE LINEARLY TO 50 KPH AND HOLD FOR 20 MINUTES
ACCELERATE LINEARLY TO 90 KPH AND HOLD FOR 20 MINUTES
DECELERATE TO 0 KPH, IDLE FOR 5 MINUTES AND TURN OFF ENGINE

SJC.009.86

FIGURE 2

COMBUSTION AND INJECTION PROFILE SHOWING IGNITION DELAY MEASUREMENT

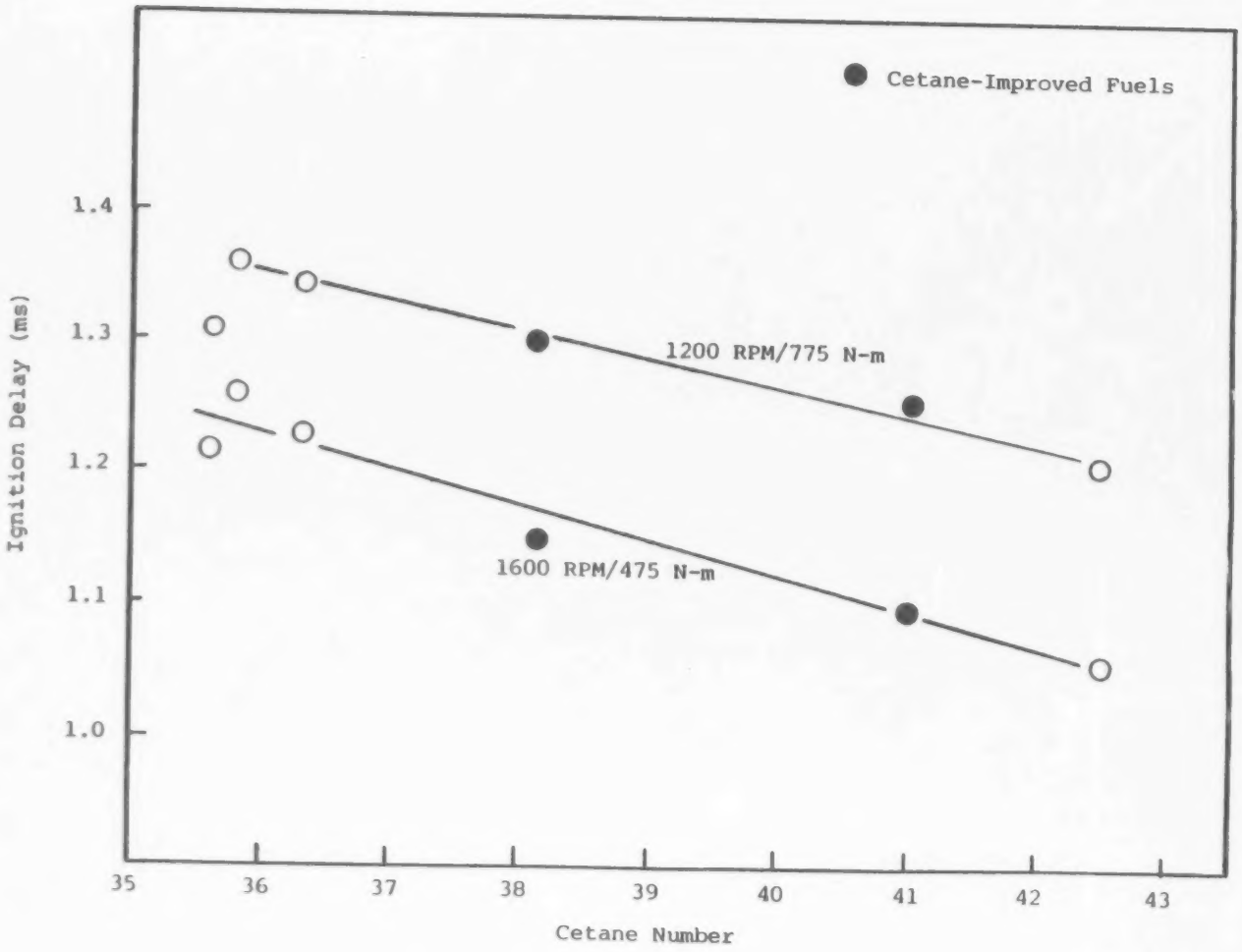



CLW.020B.86

FIGURE 3

EFFECT OF FUEL CETANE NUMBER ON IGNITION DELAY

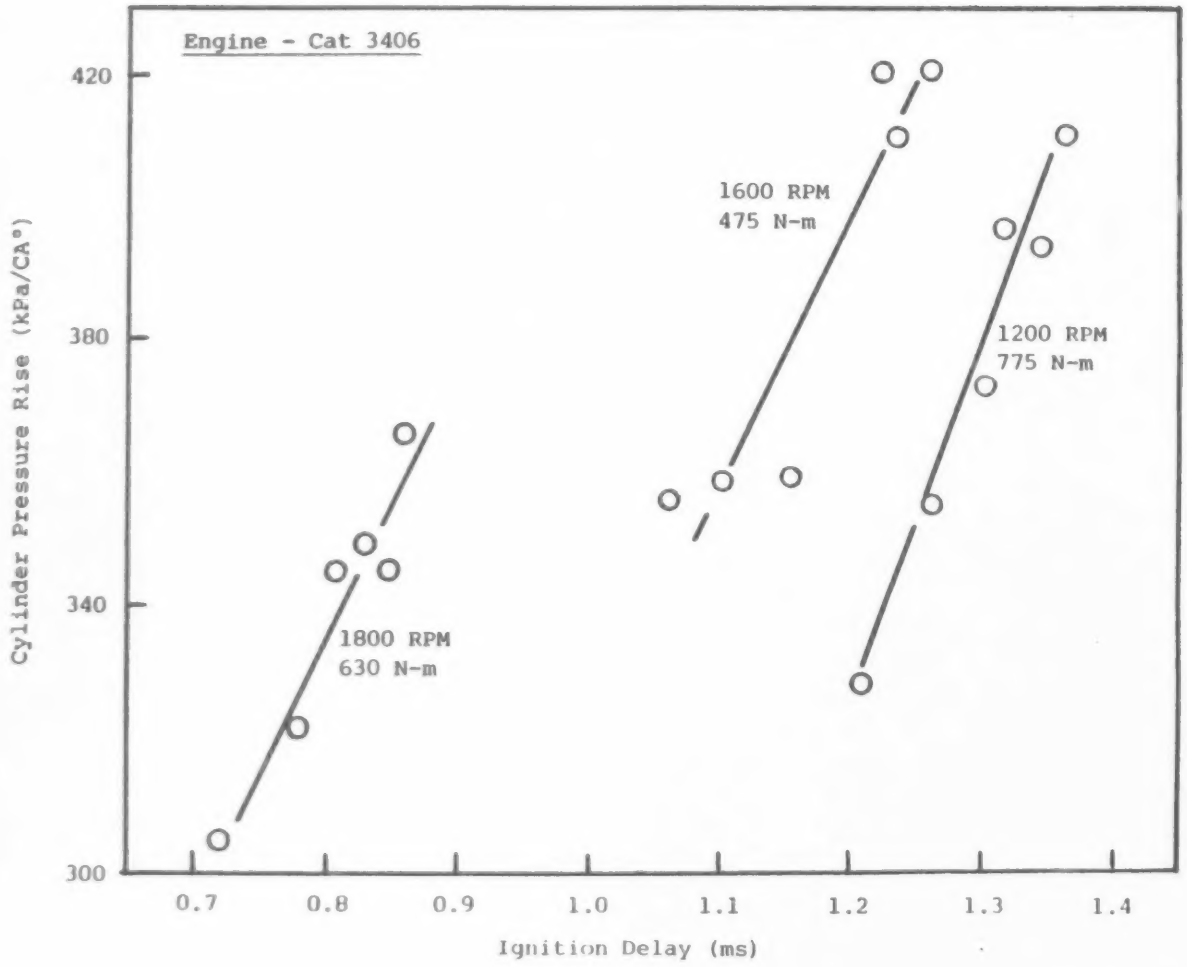
Engine - Cat 3406




CLW.068.86

FIGURE 4

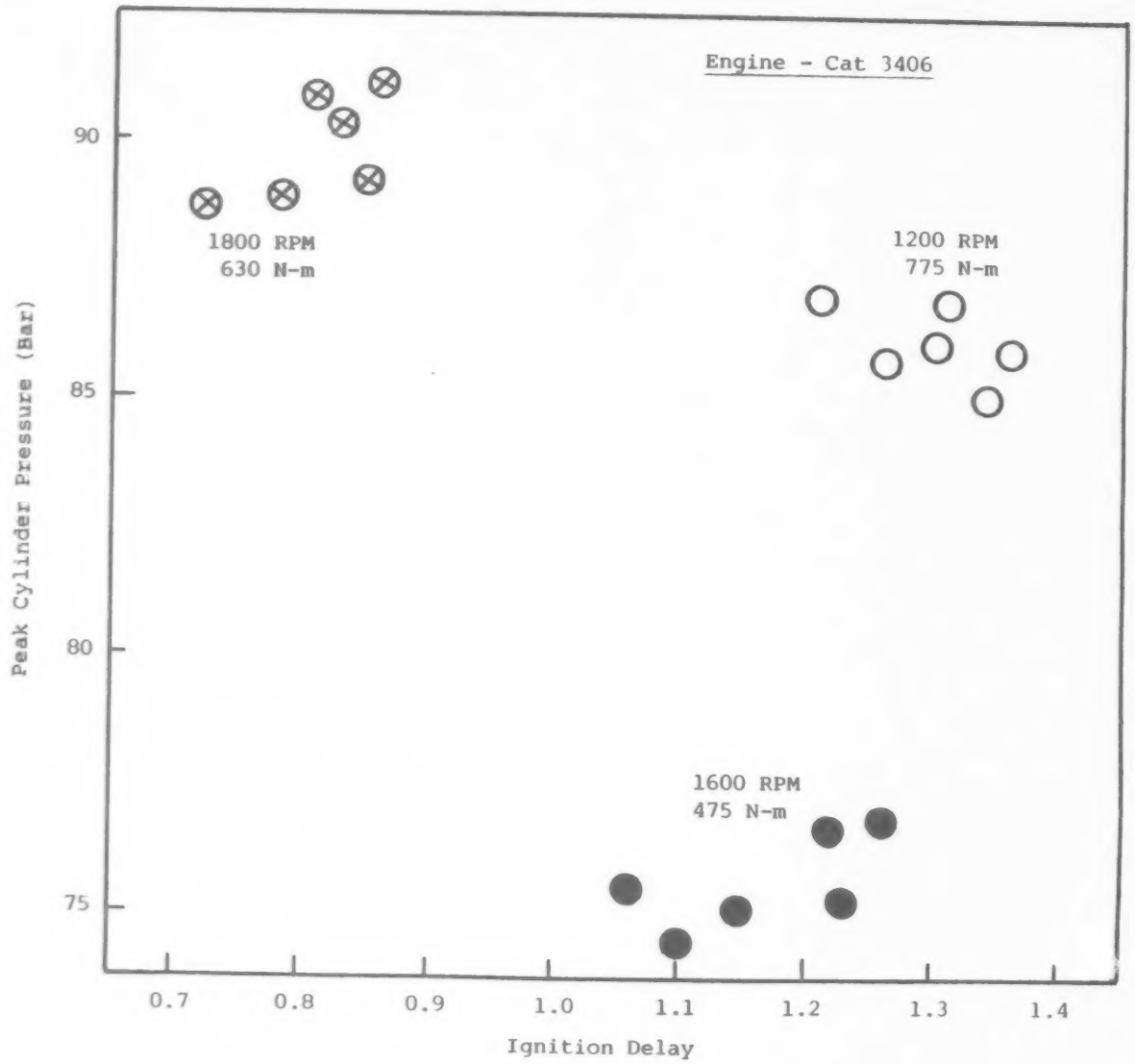
HIGHER CETANE REDUCES RATE OF CYLINDER PRESSURE RISE
AT INTERMEDIATE TORQUE LEVELS




CLW.067.86

FIGURE 5

NO CORRELATION BETWEEN PEAK CYLINDER PRESSURE AND IGNITION DELAY AT INTERMEDIATE TORQUE LEVELS

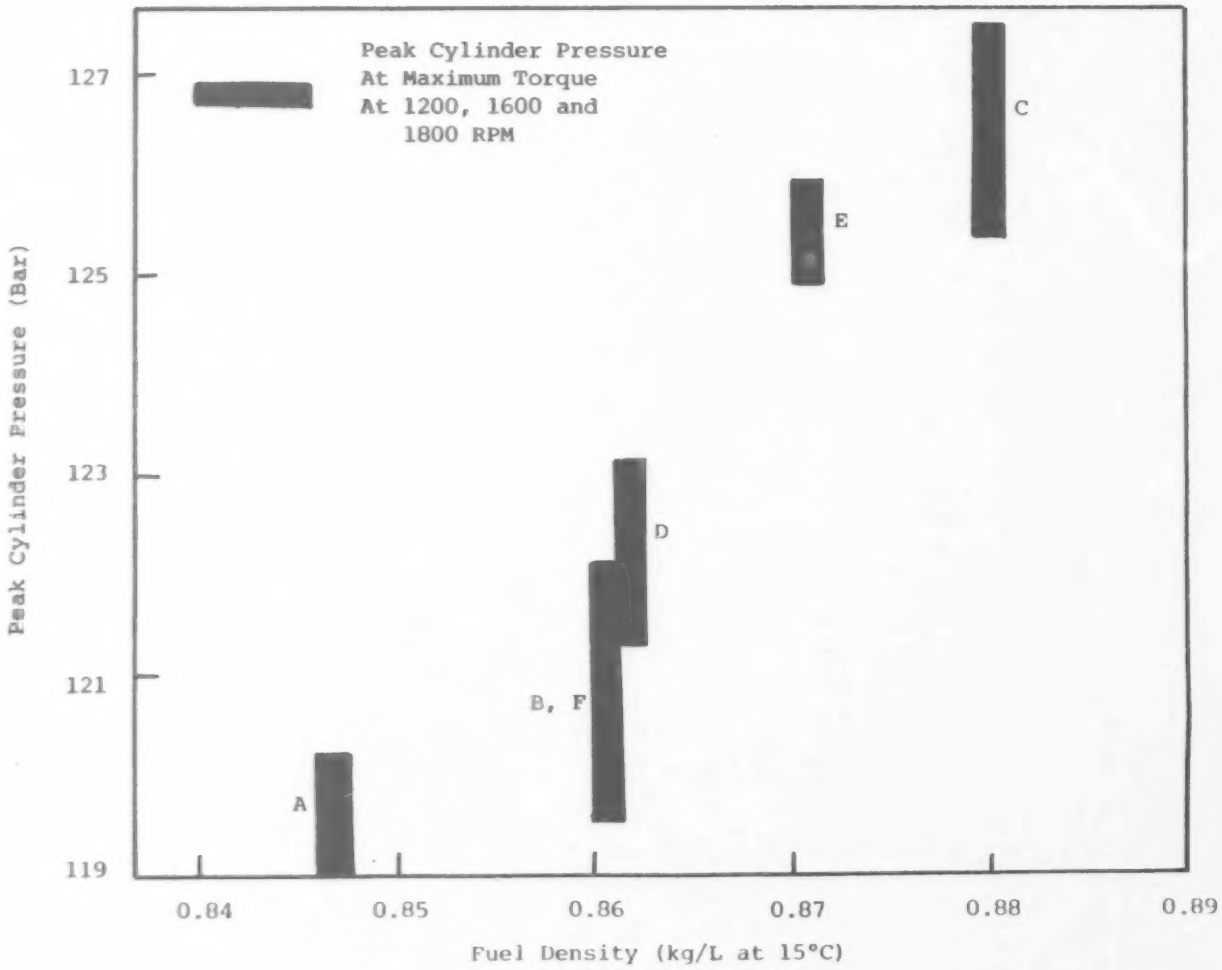



CLW.068.86

FIGURE 6

HIGHER FUEL DENSITY RESULTS
IN HIGHER PEAK CYLINDER PRESSURE AT FULL RACK

Engine - Cat 3406

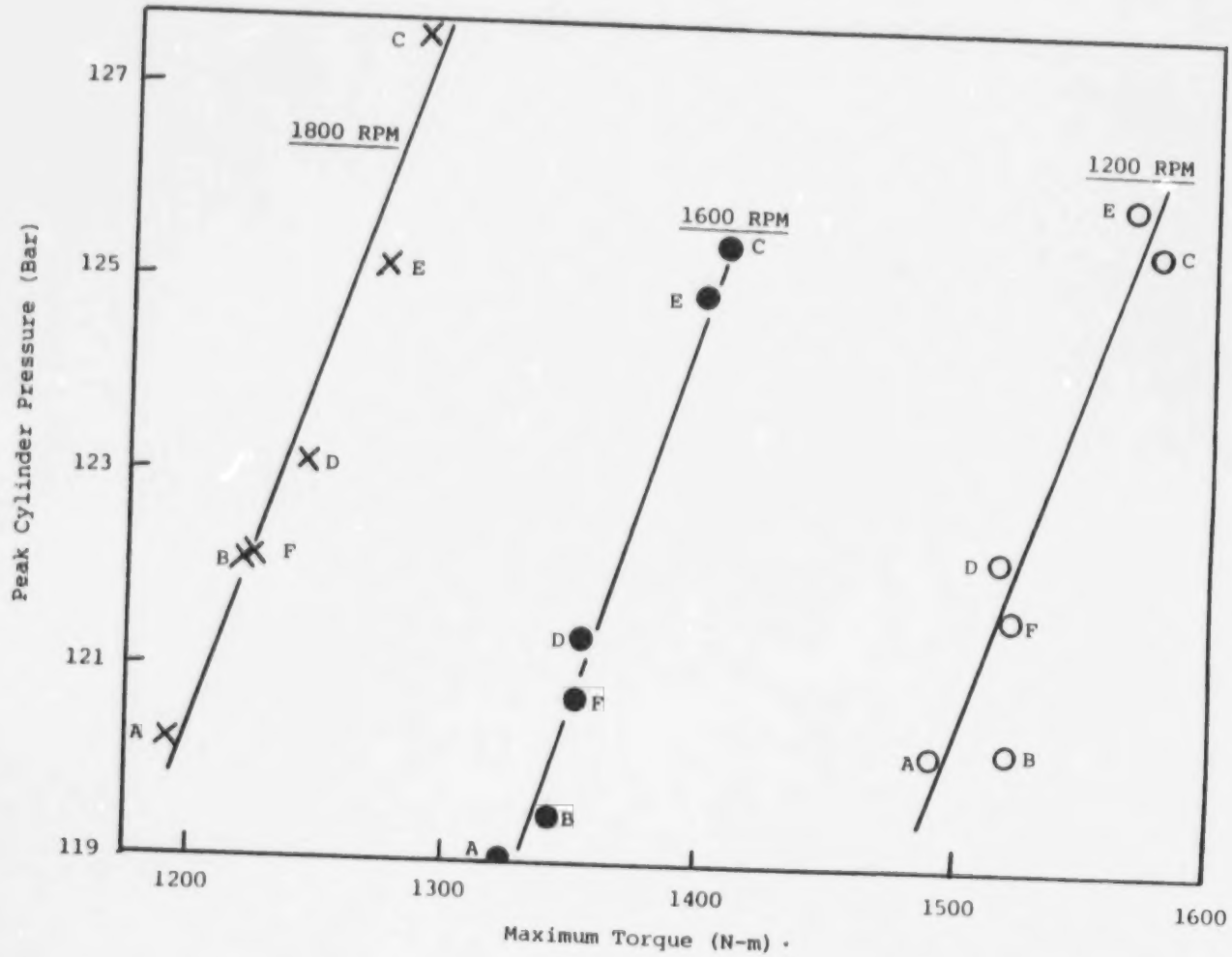



CLW.069.86

FIGURE 7

PEAK CYLINDER PRESSURE IS DIRECTLY PROPORTIONAL TO MAXIMUM TORQUE AT MAXIMUM FUELLING RATE

Engine - Cat 3406

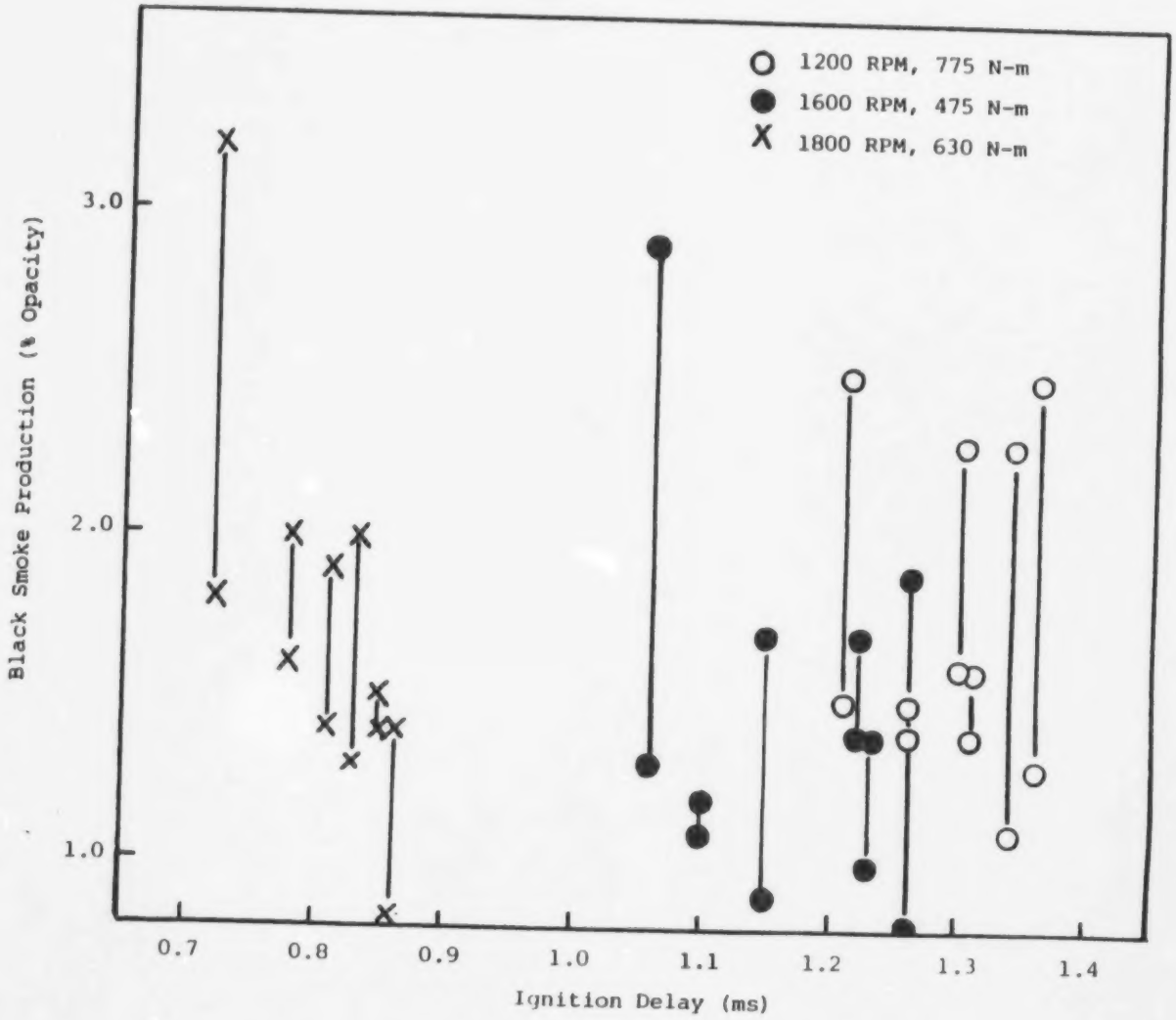



CLW.070.86

FIGURE 8

BLACK SMOKE PRODUCTION IS NOT AFFECTED BY IGNITION DELAY

Engine - Cat 3406

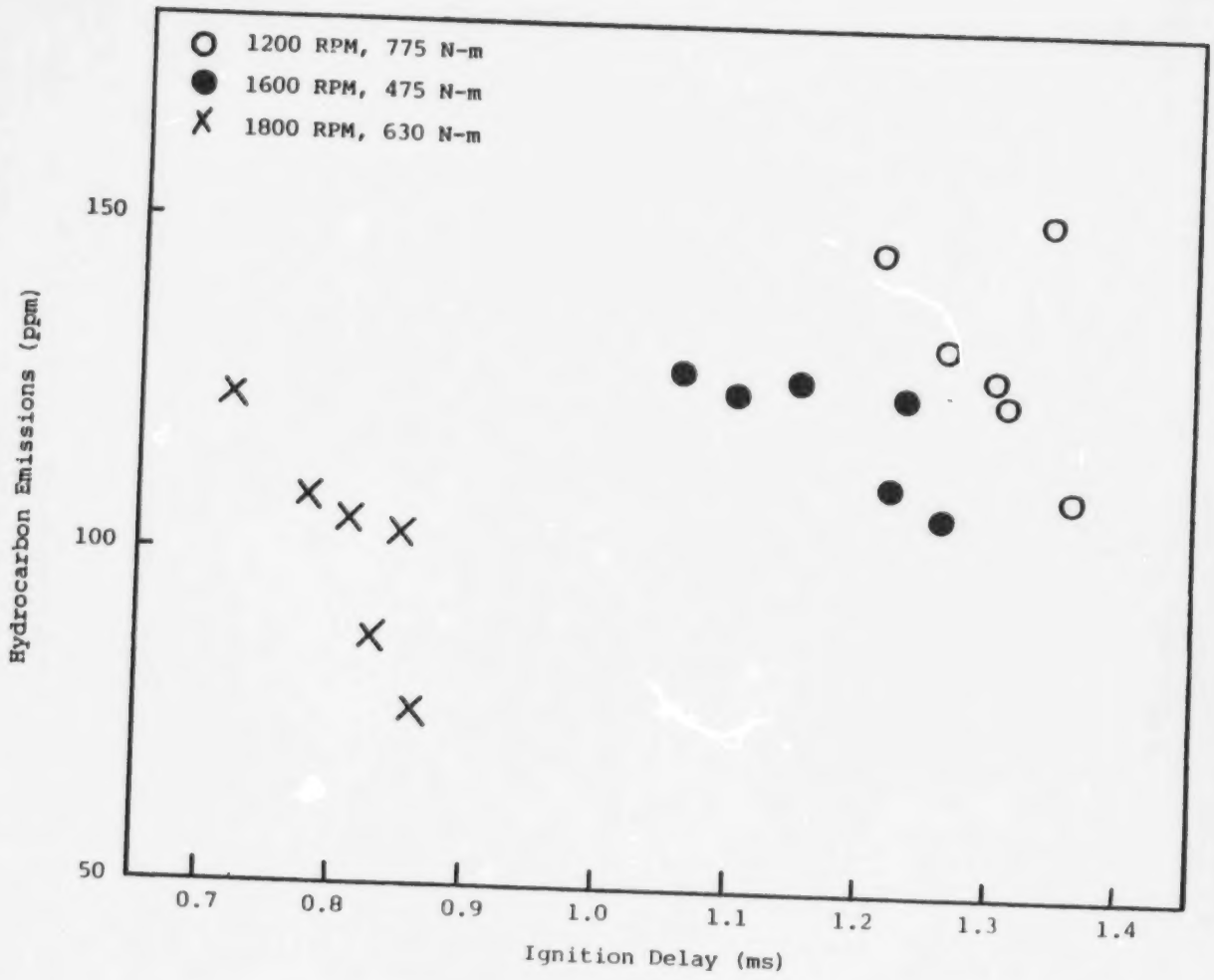



CLW.071.86

FIGURE 9

LONGER IGNITION DELAY APPARENTLY REDUCES HYDROCARBON EMISSIONS

Engine - Cat 3406

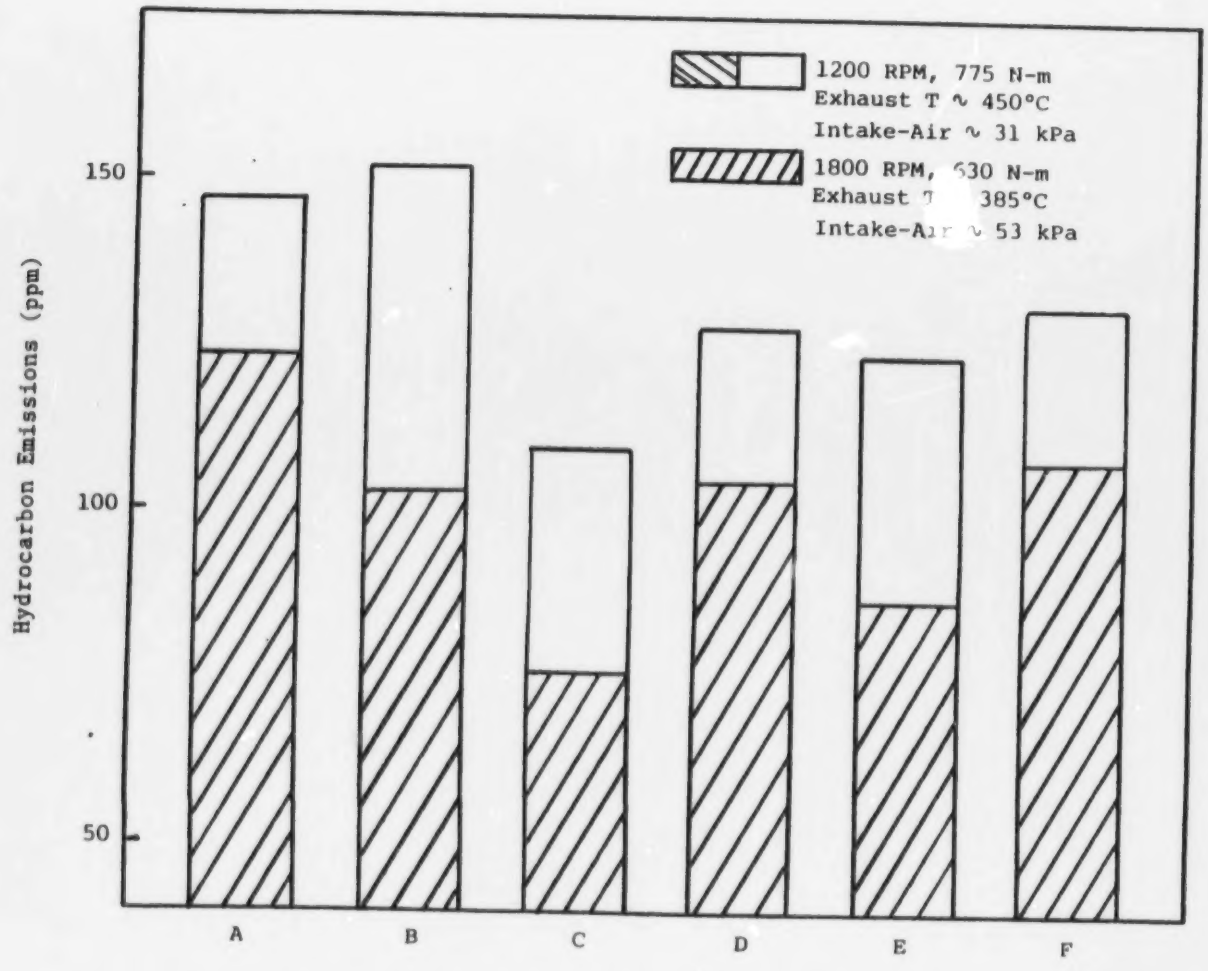



CLW.072.86

FIGURE 10

HIGHER INTAKE-AIR PRESSURE IS MORE IMPORTANT THAN HIGHER COMBUSTION TEMPERATURE IN AFFECTING HC EMISSIONS

Engine - Cat 3406

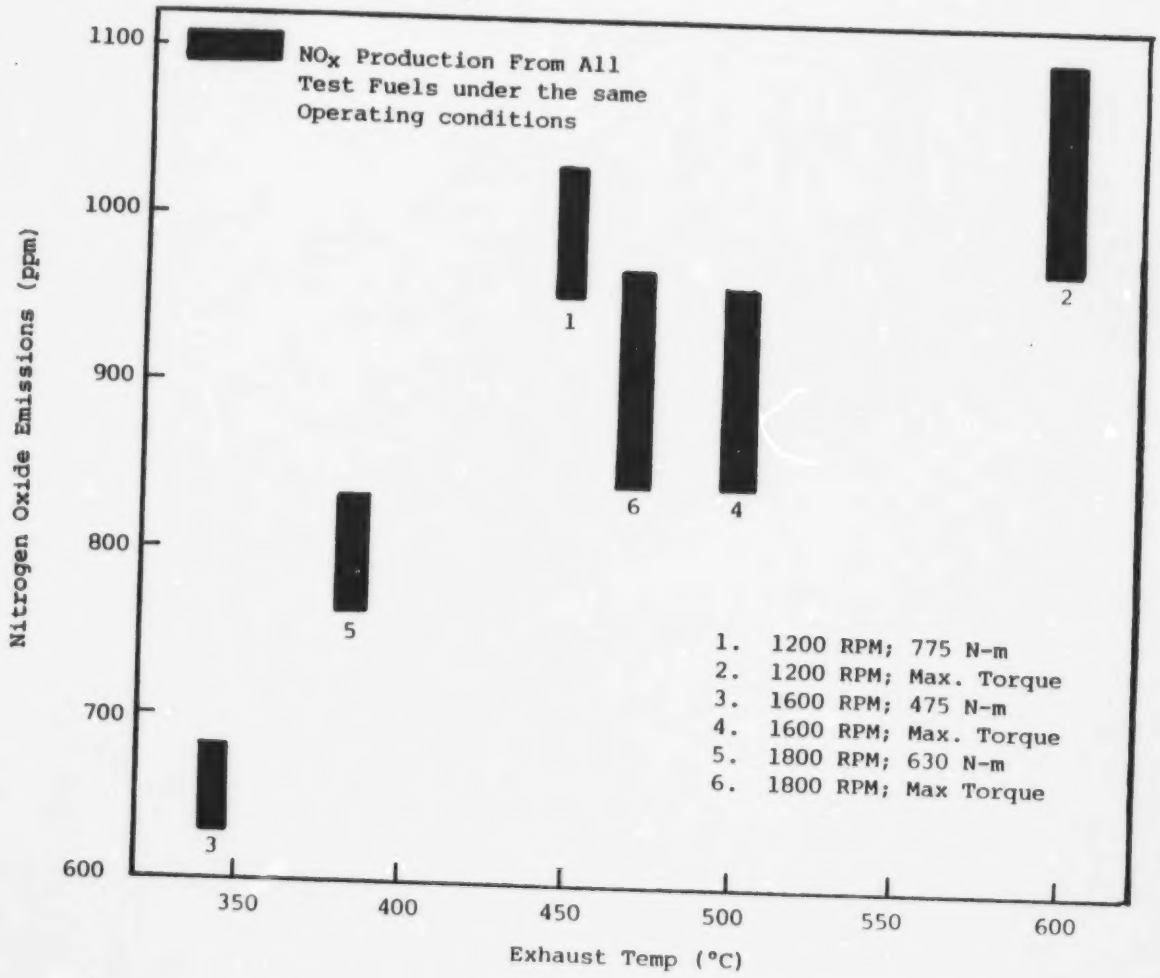



CLW.073.86

FIGURE 11

COMBUSTION TEMPERATURE HAS MUCH GREATER EFFECT ON $NO_X$ EMISSIONS THAN FUEL PARAMETERS

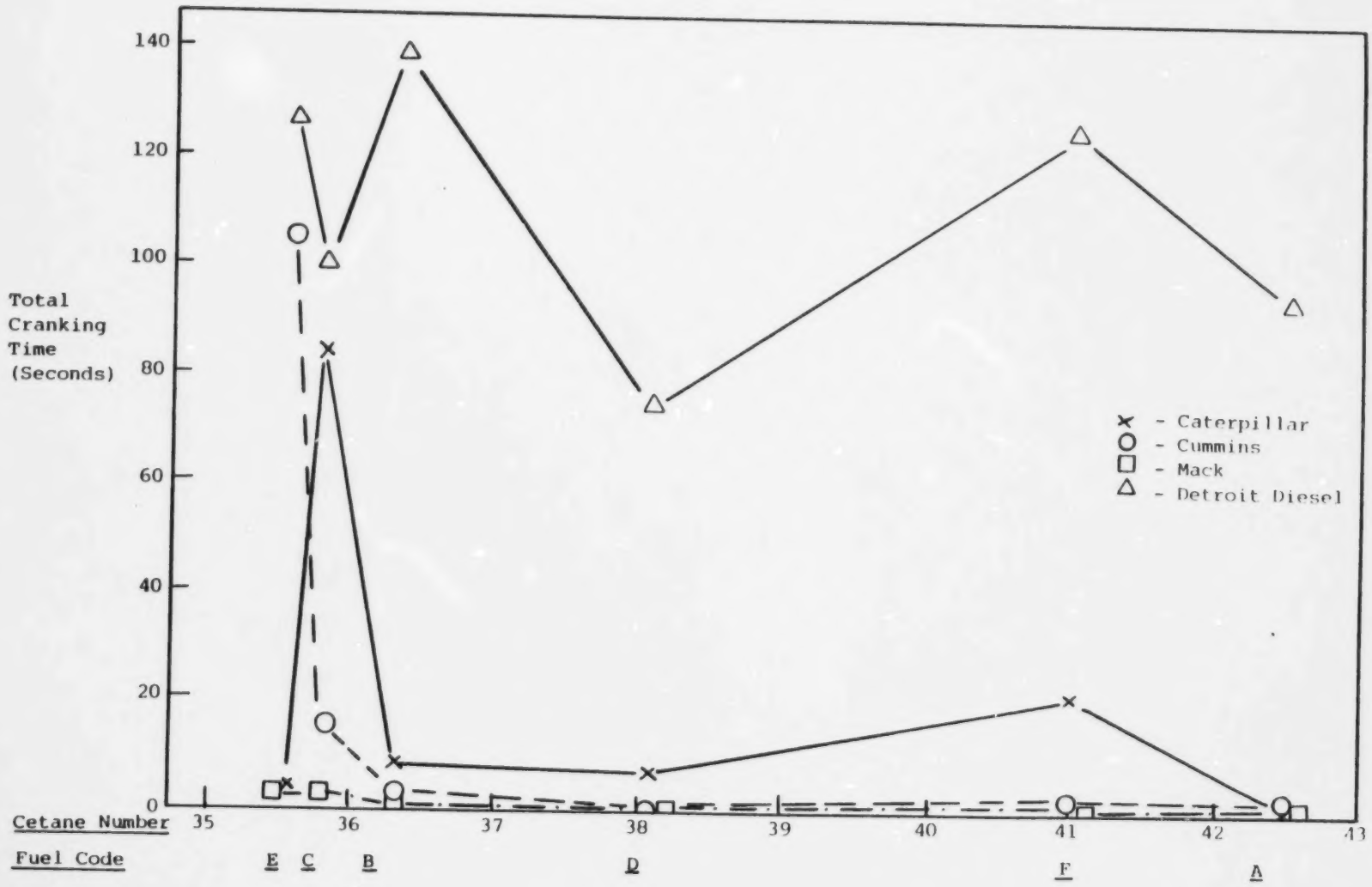
Engine - Cat 3406




CLW.074.86

FIGURE 12

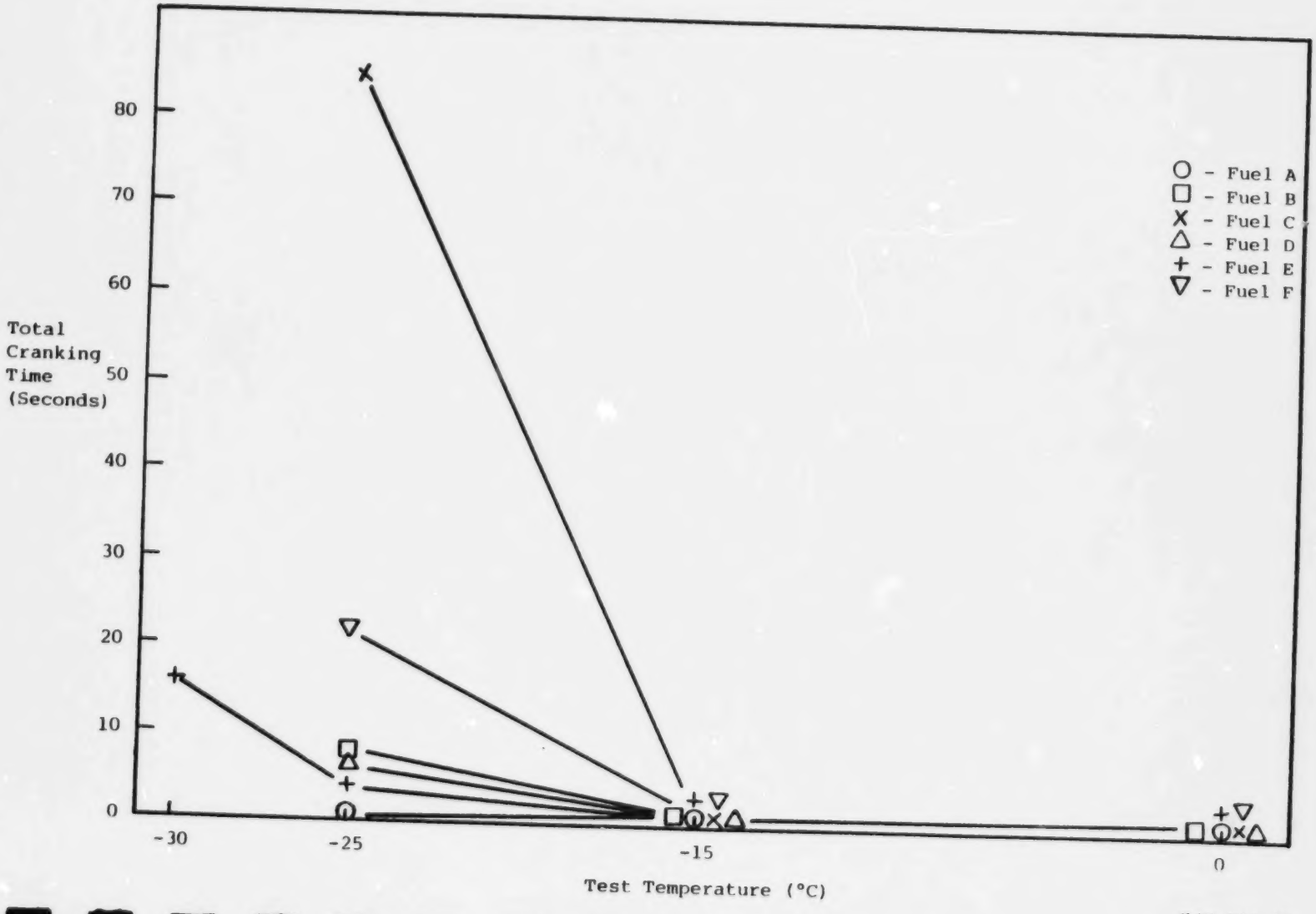
THE EFFECT OF FUEL QUALITY AND ENGINE DESIGN
ON COLD STARTING AT -25°C




SJC.010.86

FIGURE 13

THE EFFECT OF FUEL QUALITY AND TEMPERATURE
ON COLD STARTING OF THE CATERPILLAR 3406






SJC.011.86

FIGURE 14

THE EFFECT OF FUEL QUALITY AND TEMPERATURE ON COLD STARTING OF THE CUMMINS NTC 400

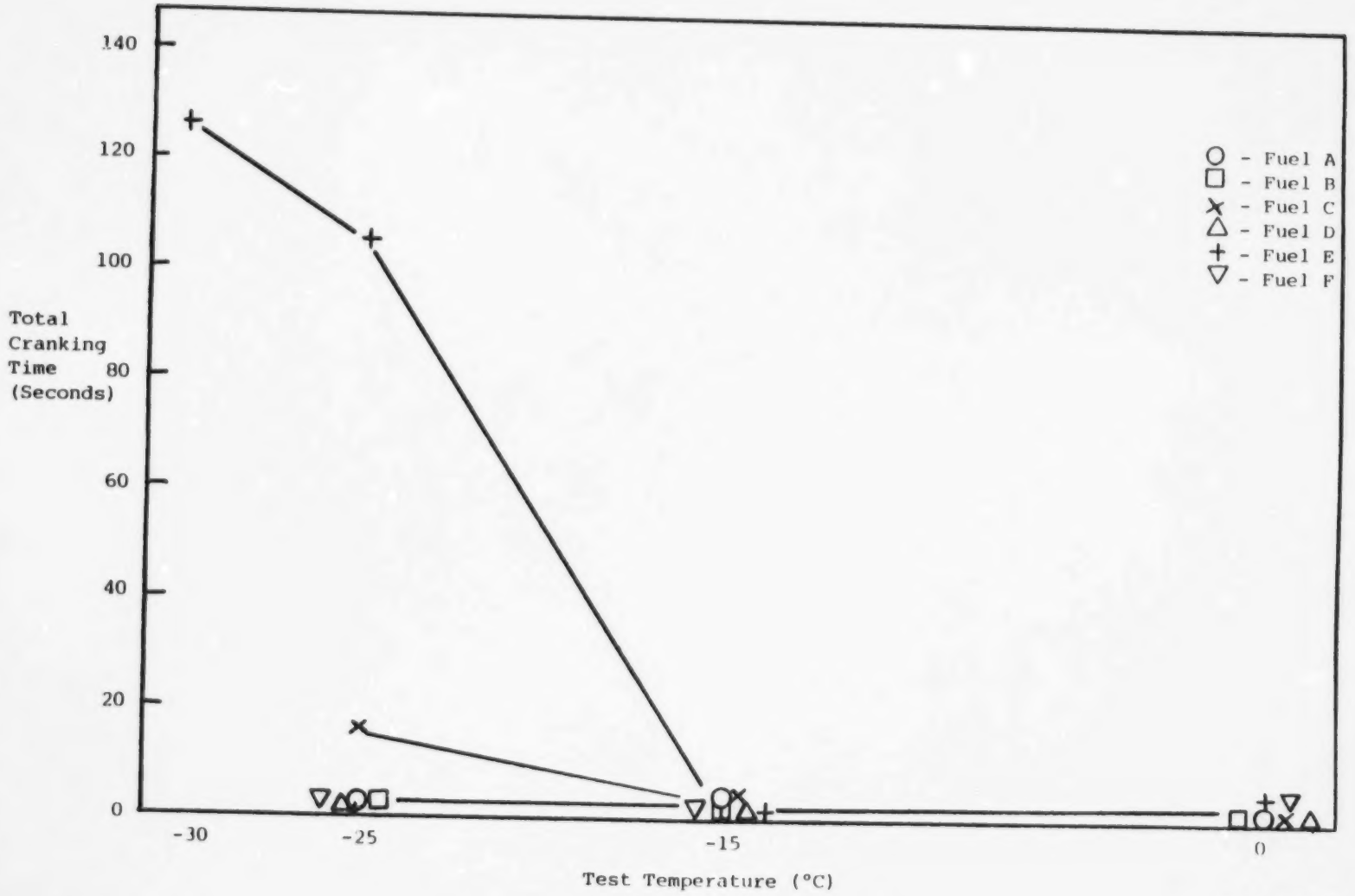


FIGURE 15

THE EFFECT OF FUEL QUALITY AND TEMPERATURE ON COLD STARTING OF THE DETROIT DIESEL 8V92

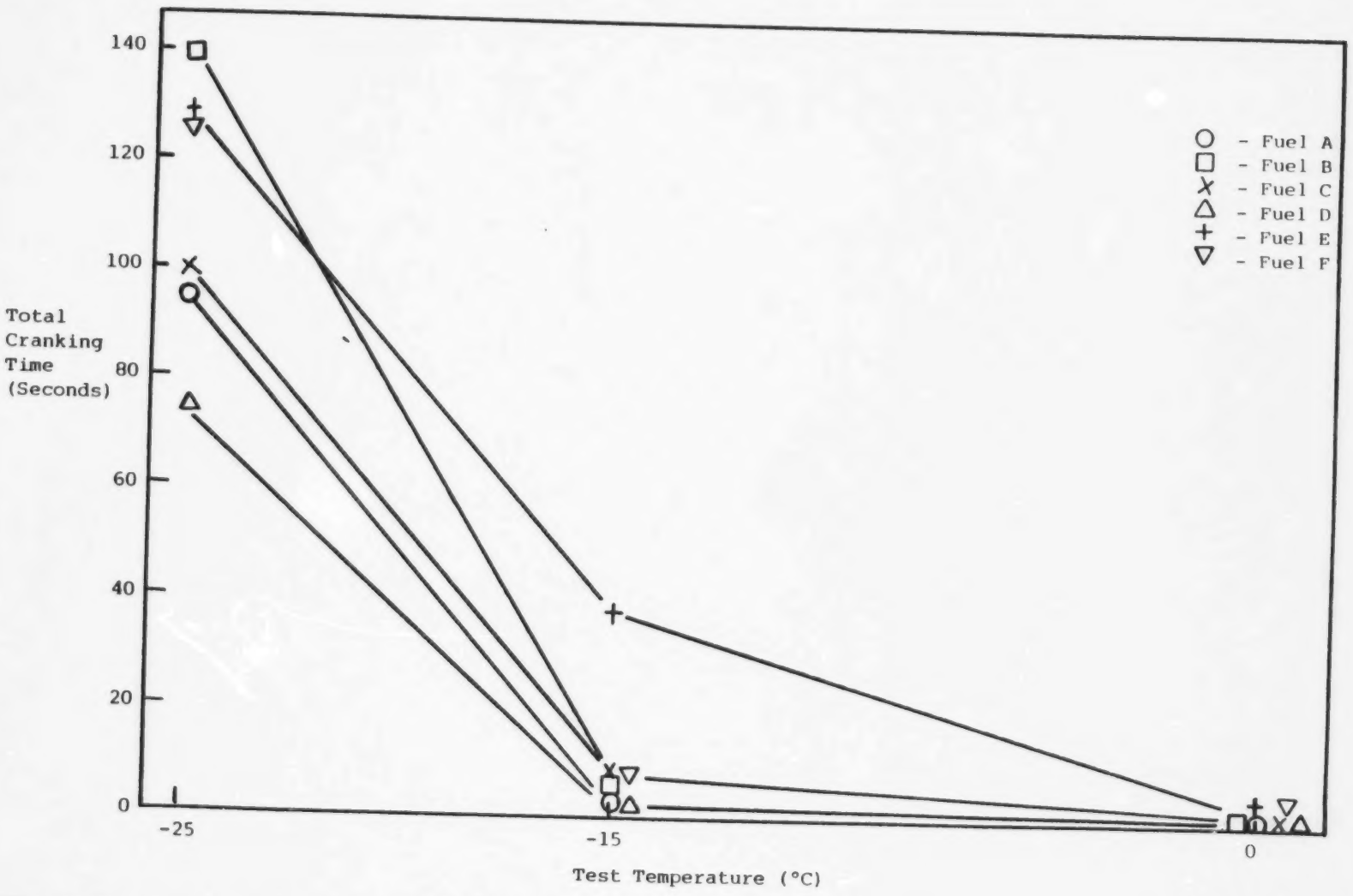
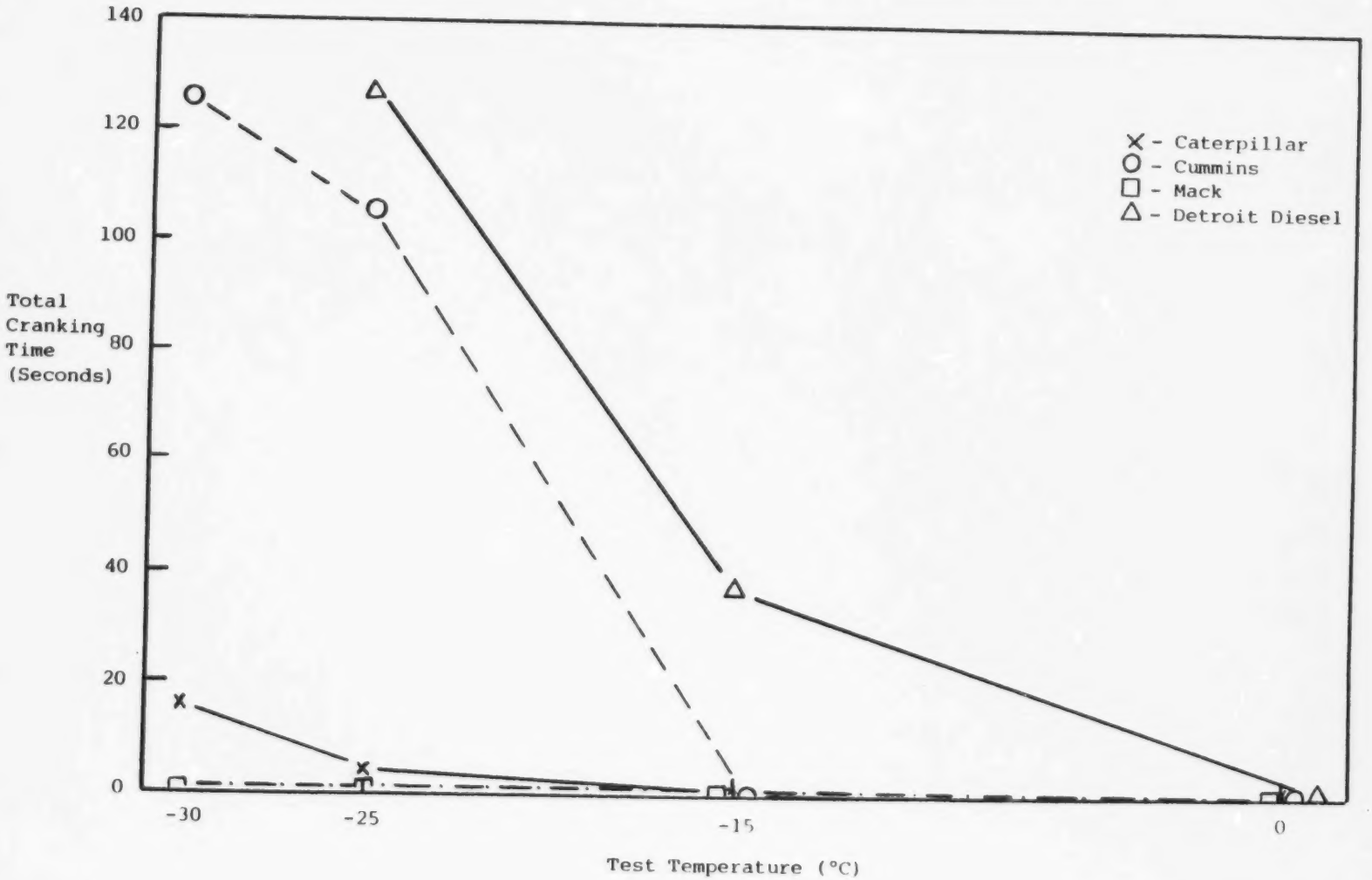


FIGURE 16

THE EFFECT OF ENGINE DESIGN AND TEMPERATURE ON COLD STARTING WITH FUEL E




SJC.014.86

FIGURE 17

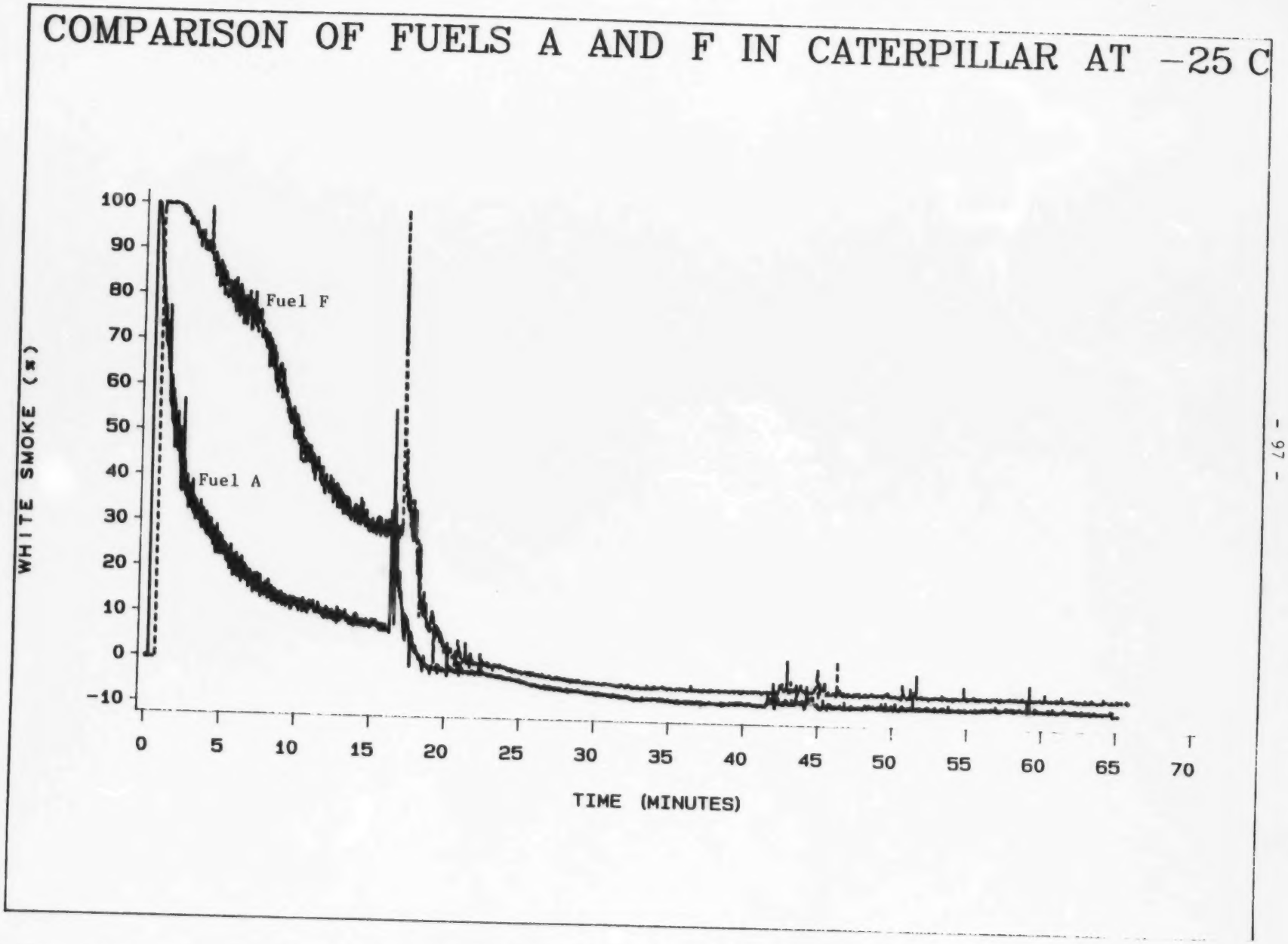

COMPARISON OF FUELS A AND F IN CATERPILLAR AT -25 C
WHITE SMOKE (%)
100
90
80
70
60
50
40
30
20
10
0
-10
Fuel F
Fuel A
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
TIME (MINUTES)

FIGURE 18

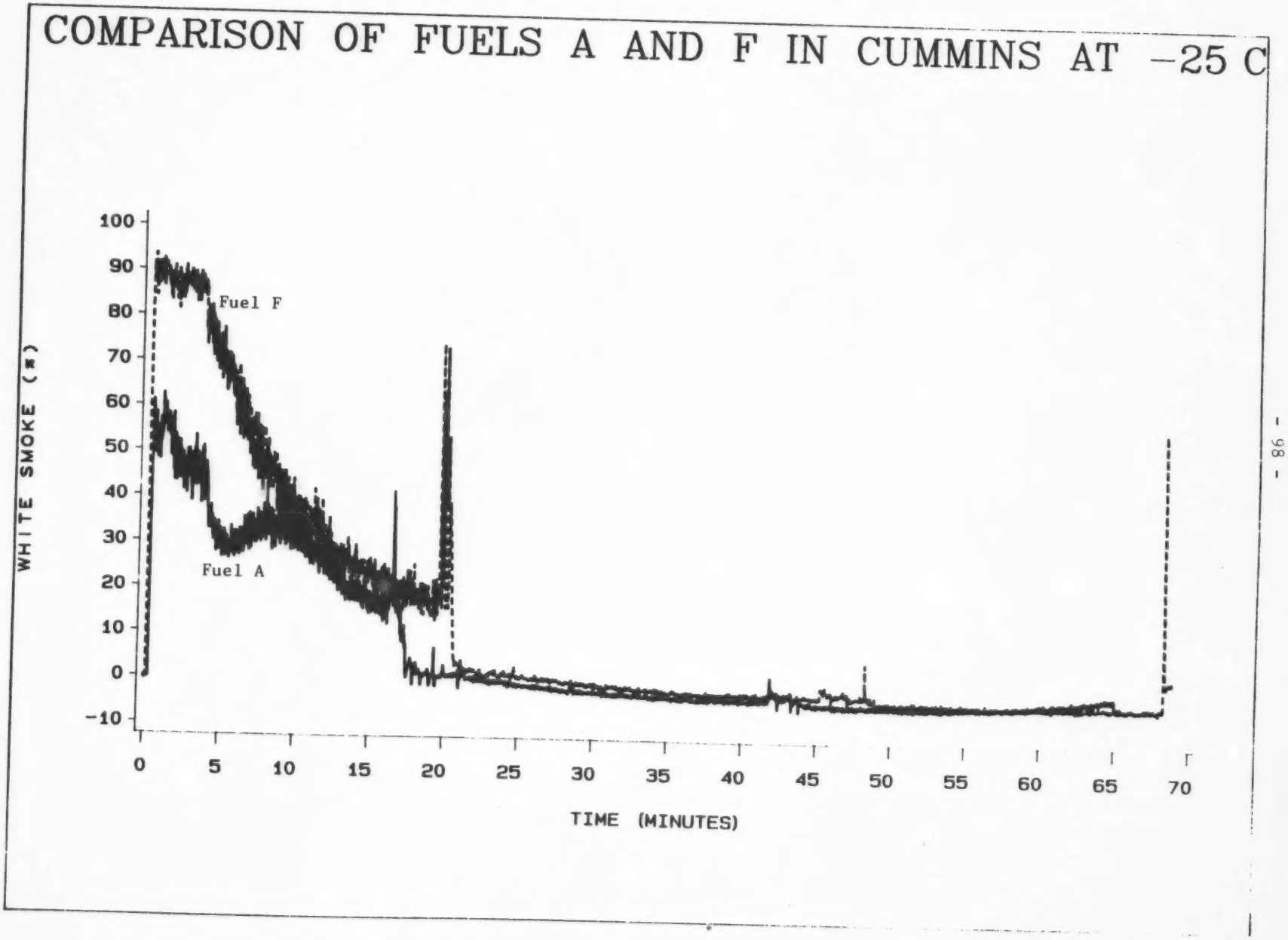

COMPARISON OF FUELS A AND F IN CUMMINS AT -25 C
WHITE SMOKE (%)
100
90
80
70
60
50
40
30
20
10
0
-10
Fuel F
Fuel A
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
TIME (MINUTES)

FIGURE 19

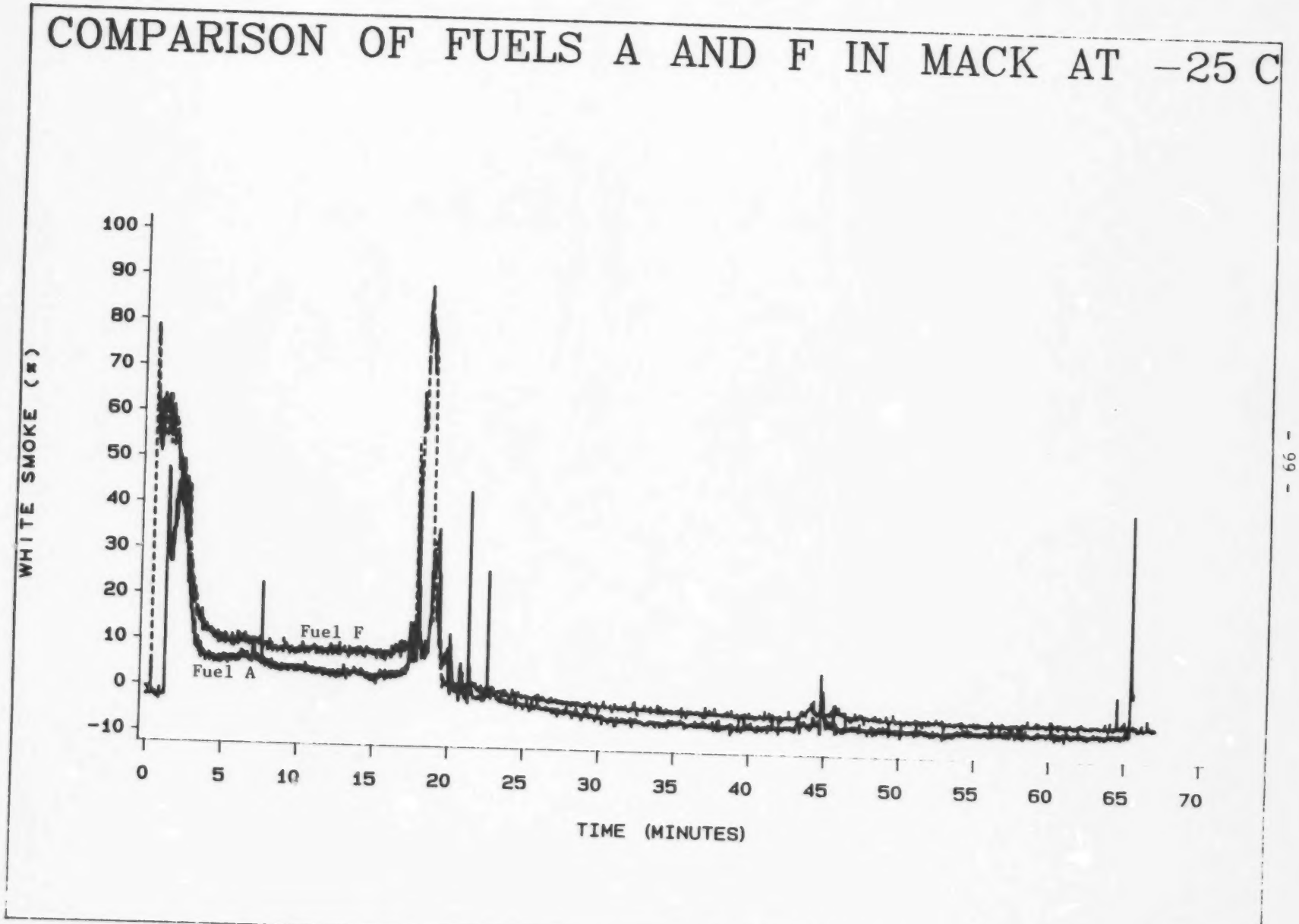

COMPARISON OF FUELS A AND F IN MACK AT -25 C
WHITE SMOKE (%)
100
90
80
70
60
50
40
30
20
10
0
-10
Fuel F
Fuel A
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
TIME (MINUTES)

FIGURE 20

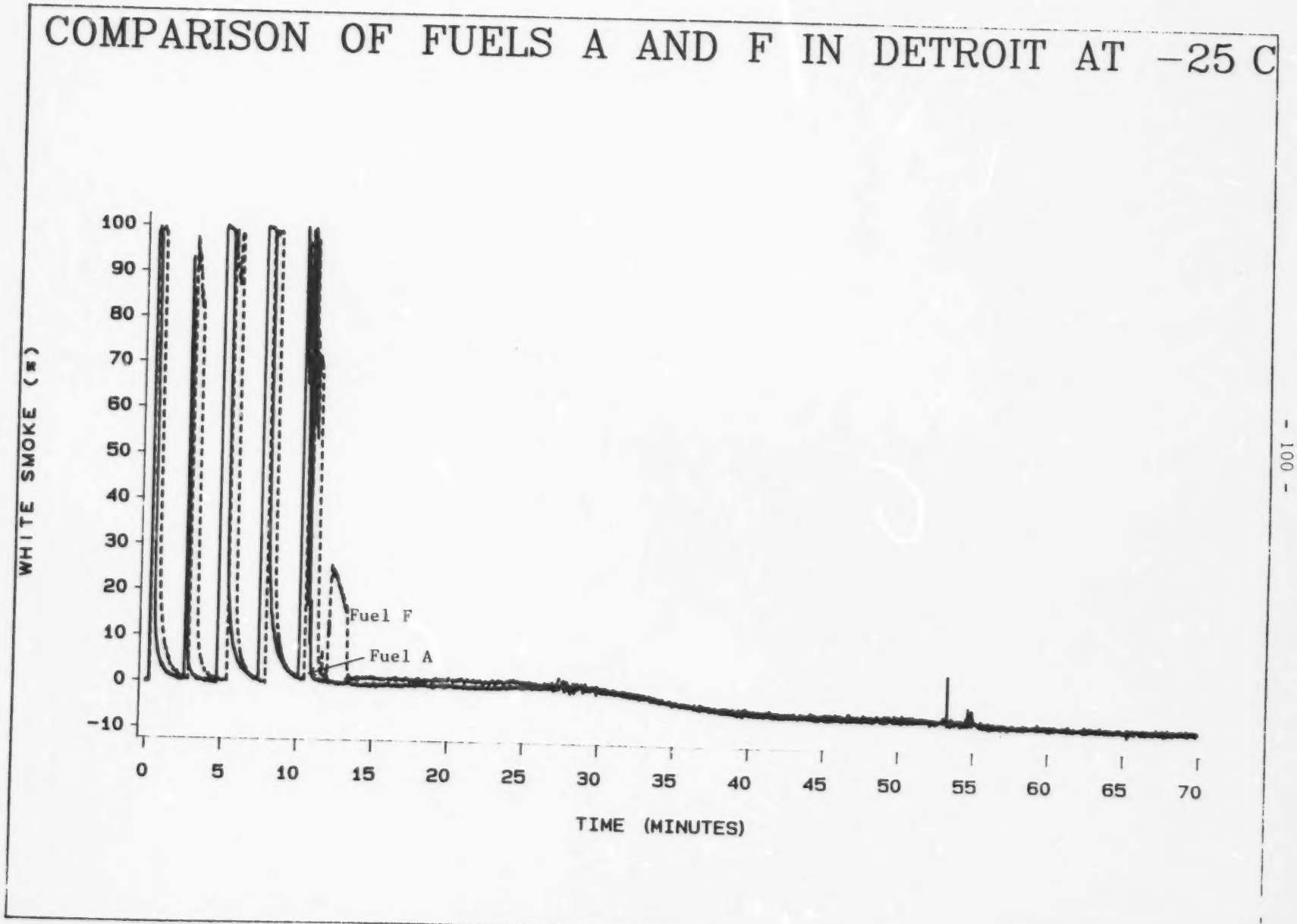

COMPARISON OF FUELS A AND F IN DETROIT AT -25 C
WHITE SMOKE (%)
100
90
80
70
60
50
40
30
20
10
0
-10
Fuel F
Fuel A
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
TIME (MINUTES)

FIGURE 21

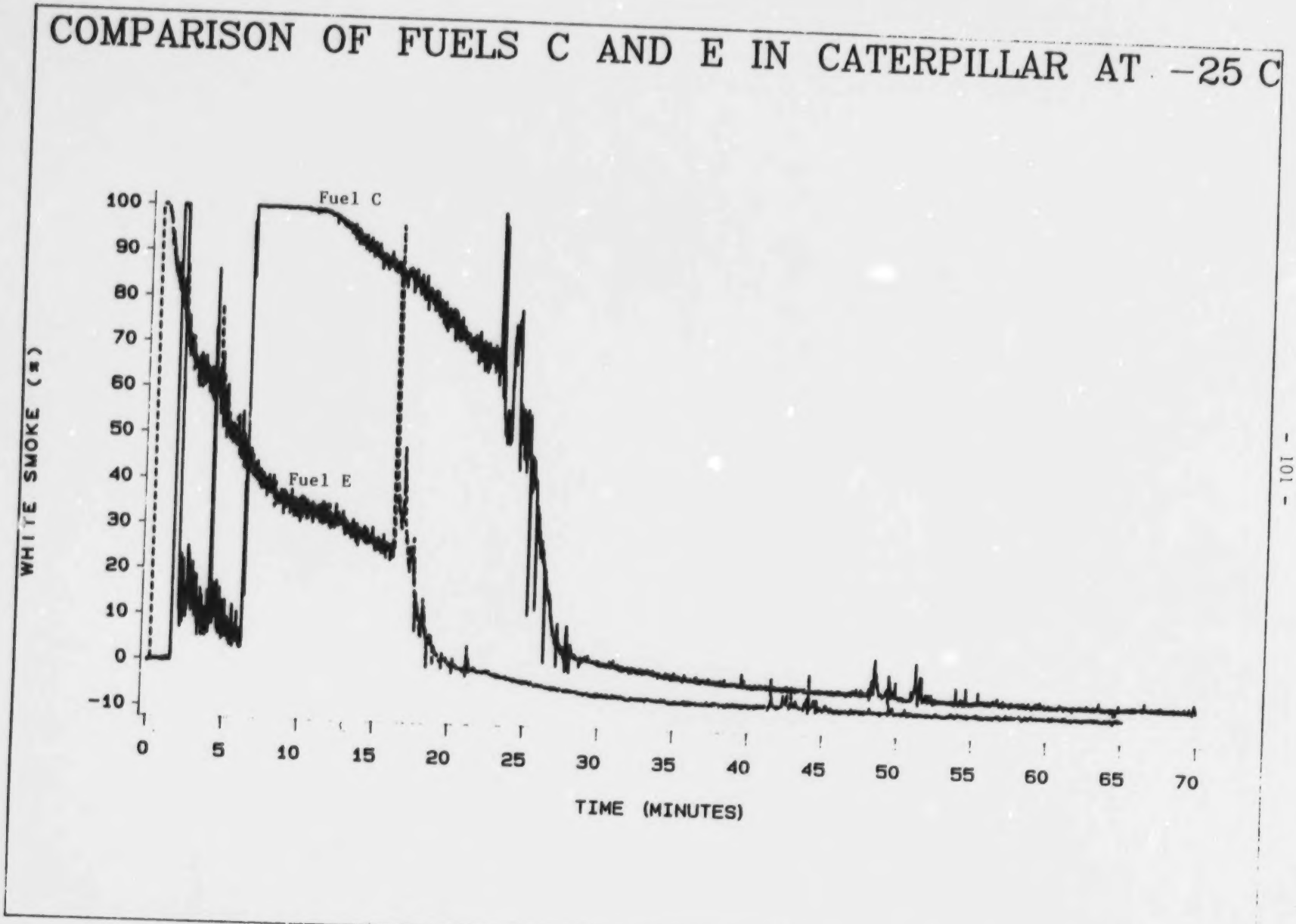

COMPARISON OF FUELS C AND E IN CATERPILLAR AT -25 C
WHITE SMOKE (%)
100
90
80
70
60
50
40
30
20
10
0
-10
Fuel C
Fuel E
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
TIME (MINUTES)

FIGURE 22

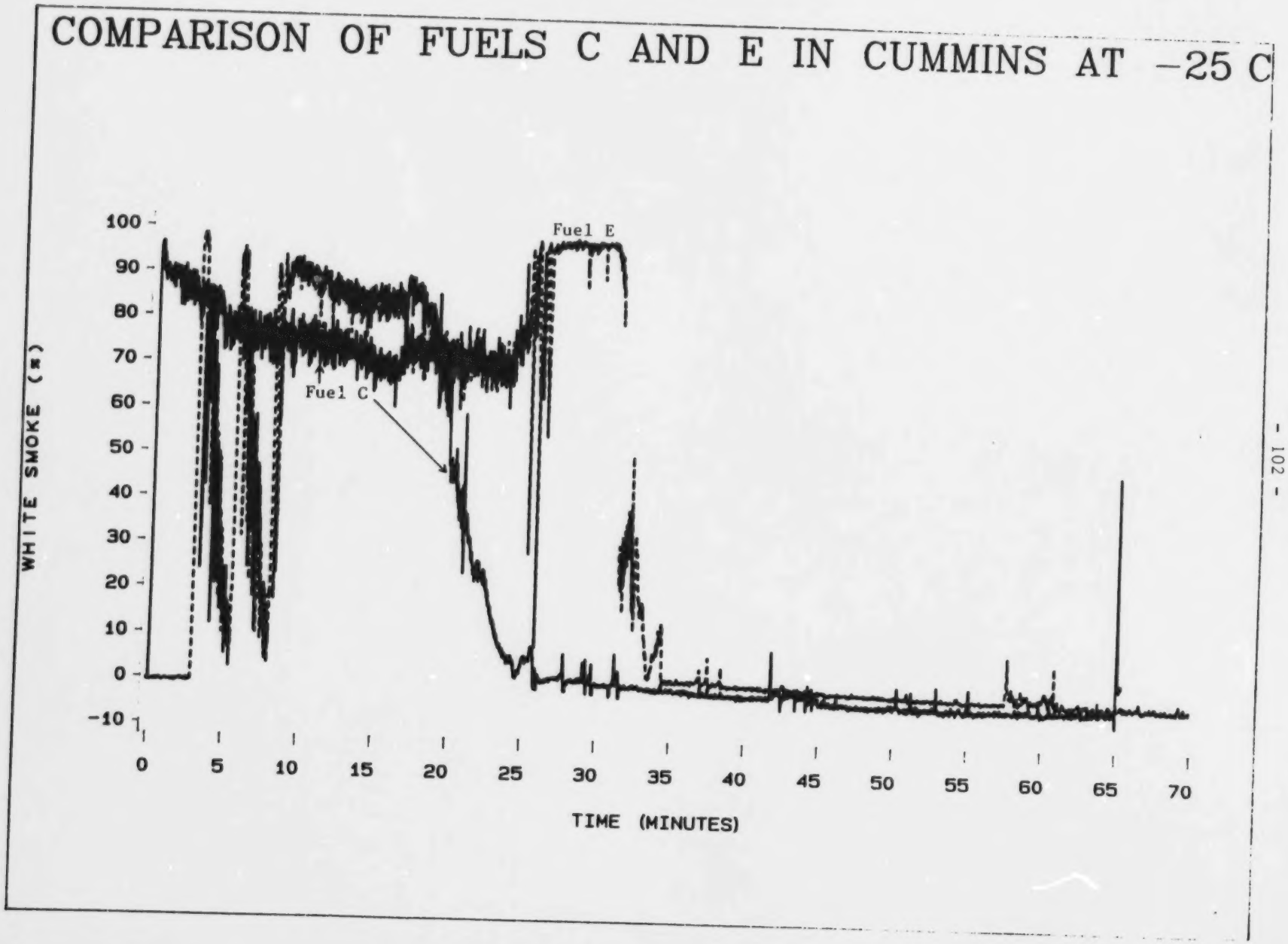

COMPARISON OF FUELS C AND E IN CUMMINS AT -25 C
WHITE SMOKE (%)
100
90
80
70
60
50
40
30
20
10
0
-10
Fuel E
Fuel C
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
TIME (MINUTES)

FIGURE 23

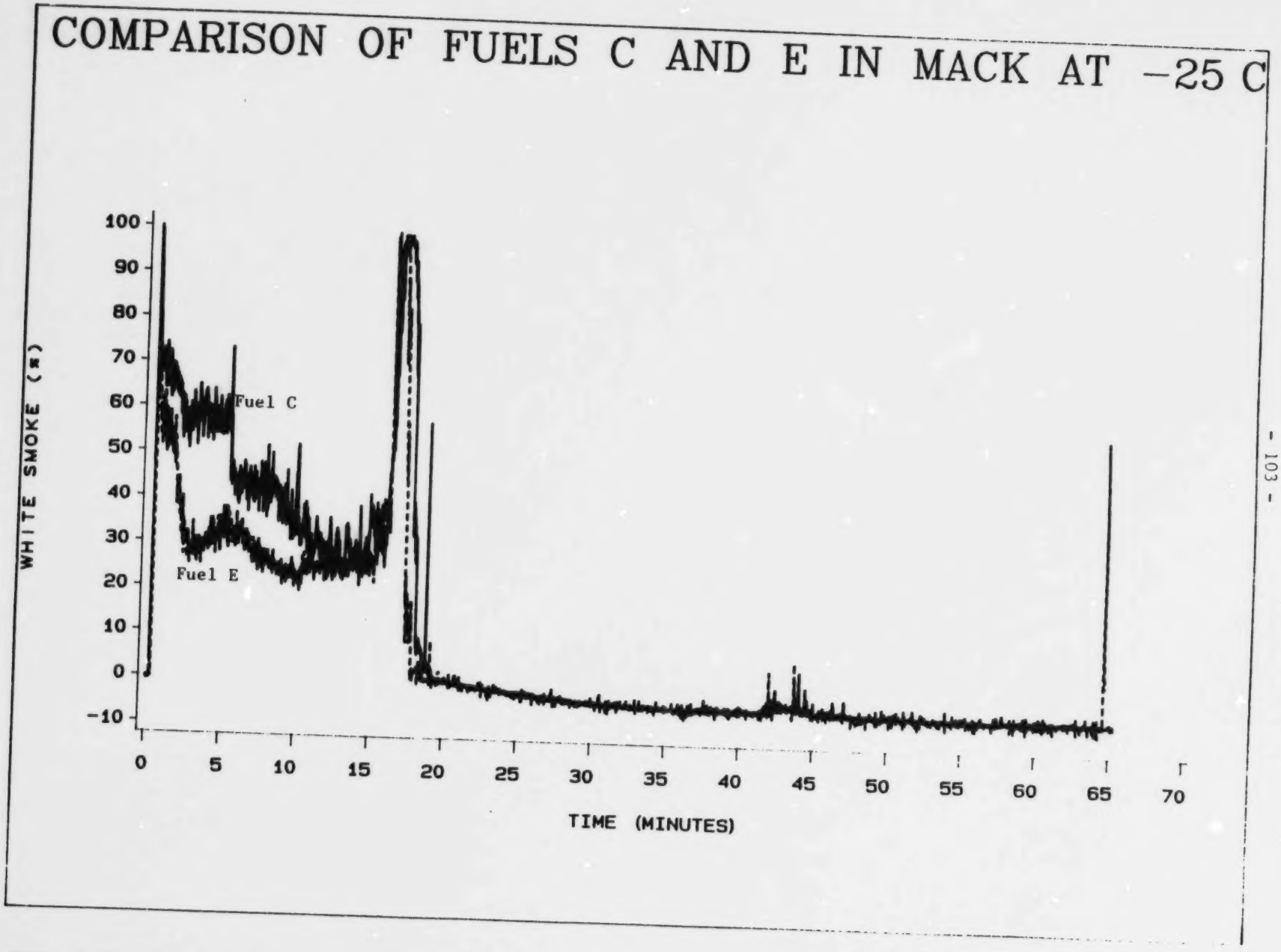

COMPARISON OF FUELS C AND E IN MACK AT -25 C
WHITE SMOKE (%)
100
90
80
70
60
50
40
30
20
10
0
-10
Fuel C
Fuel E
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
TIME (MINUTES)

FIGURE 24

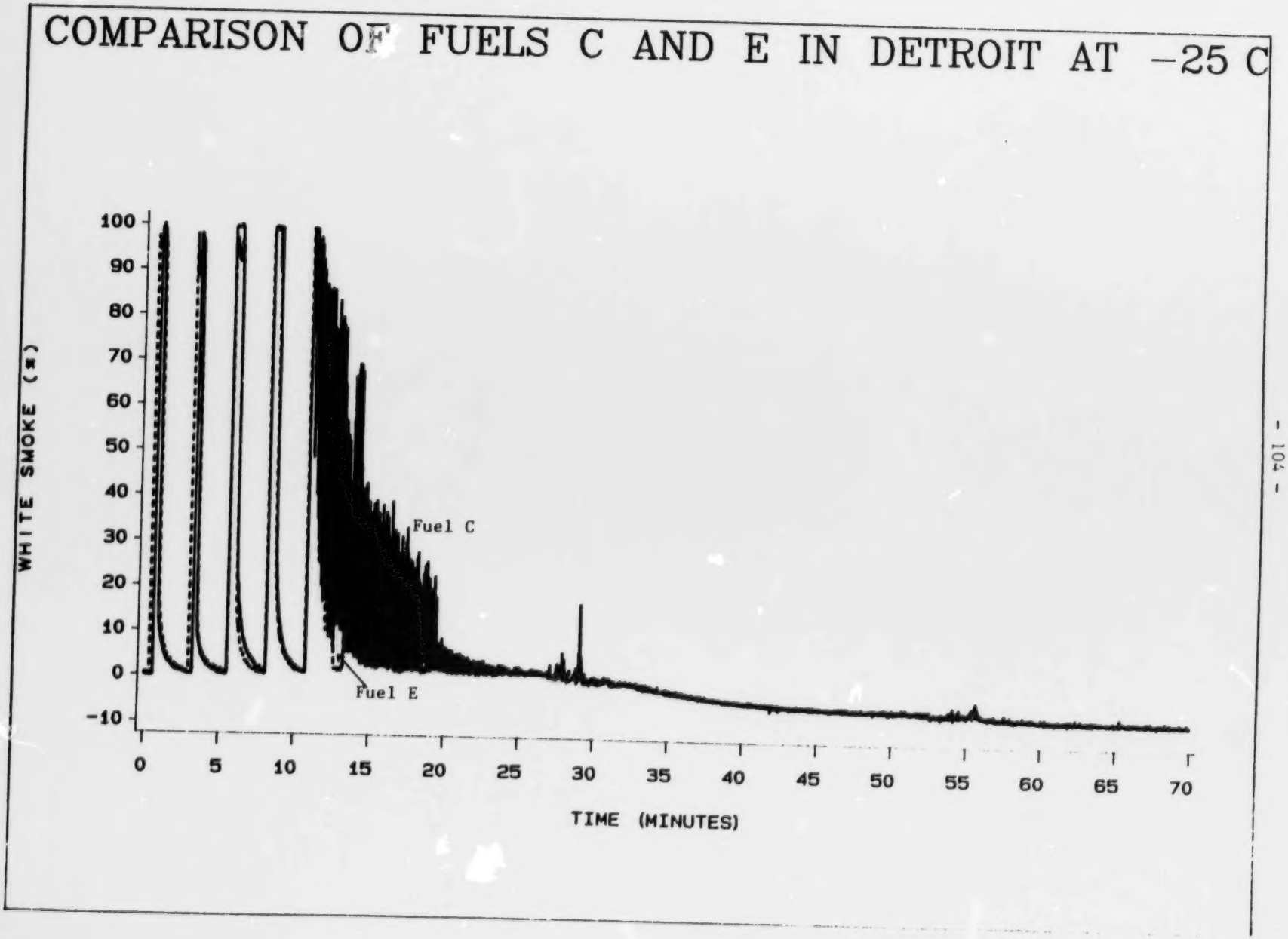

COMPARISON OF FUELS C AND E IN DETROIT AT −25 C
WHITE SMOKE (%)
100
90
80
70
60
50
40
30
20
10
0
-10
Fuel C
Fuel E
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
TIME (MINUTES)

FIGURE 25

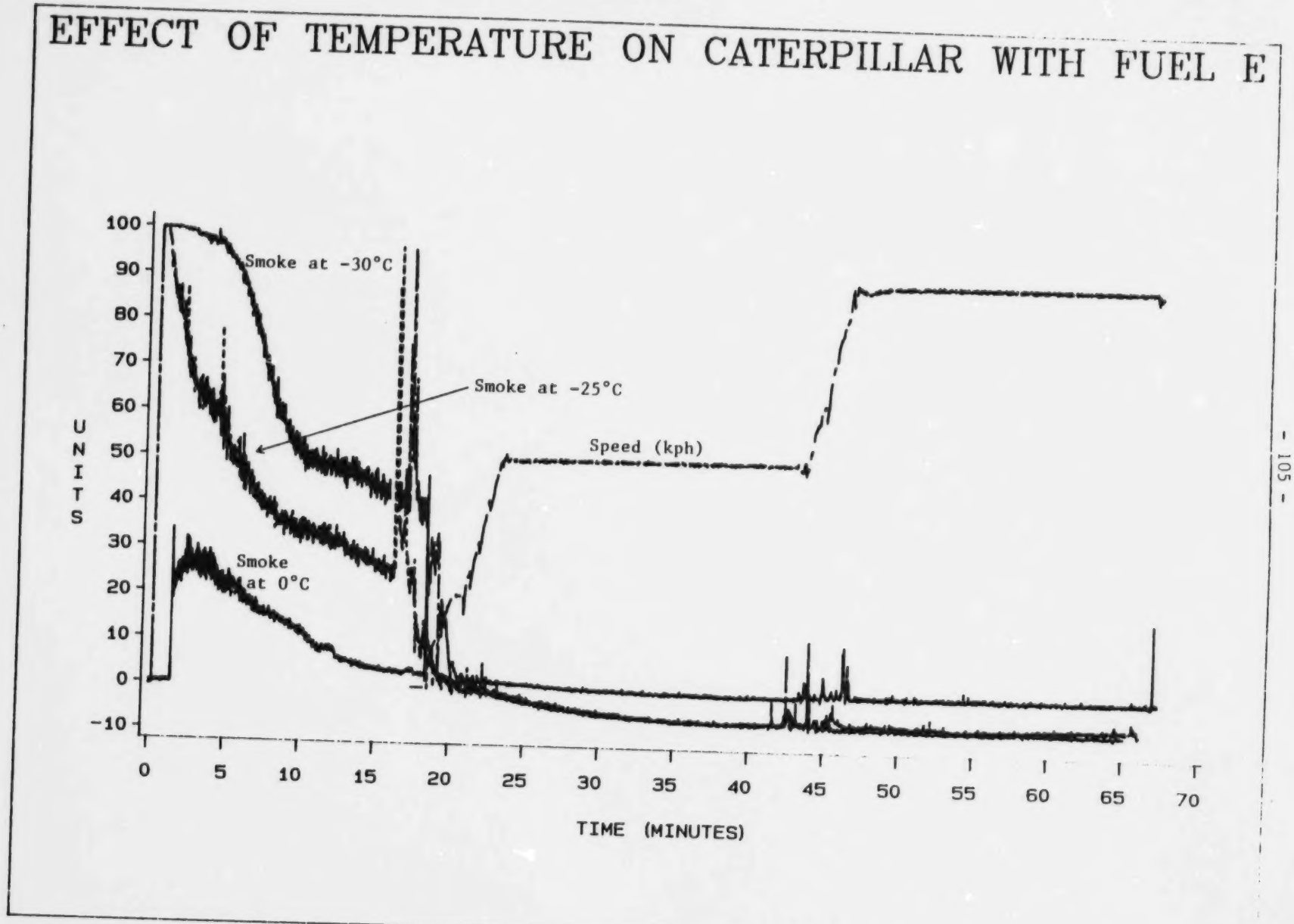

EFFECT OF TEMPERATURE ON CATERPILLAR WITH FUEL E
Smoke at -30°C
Smoke at -25°C
Speed (kph)
Smoke at 0°C
UNITS
100
90
80
70
60
50
40
30
20
10
0
-10
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
TIME (MINUTES)

FIGURE 26

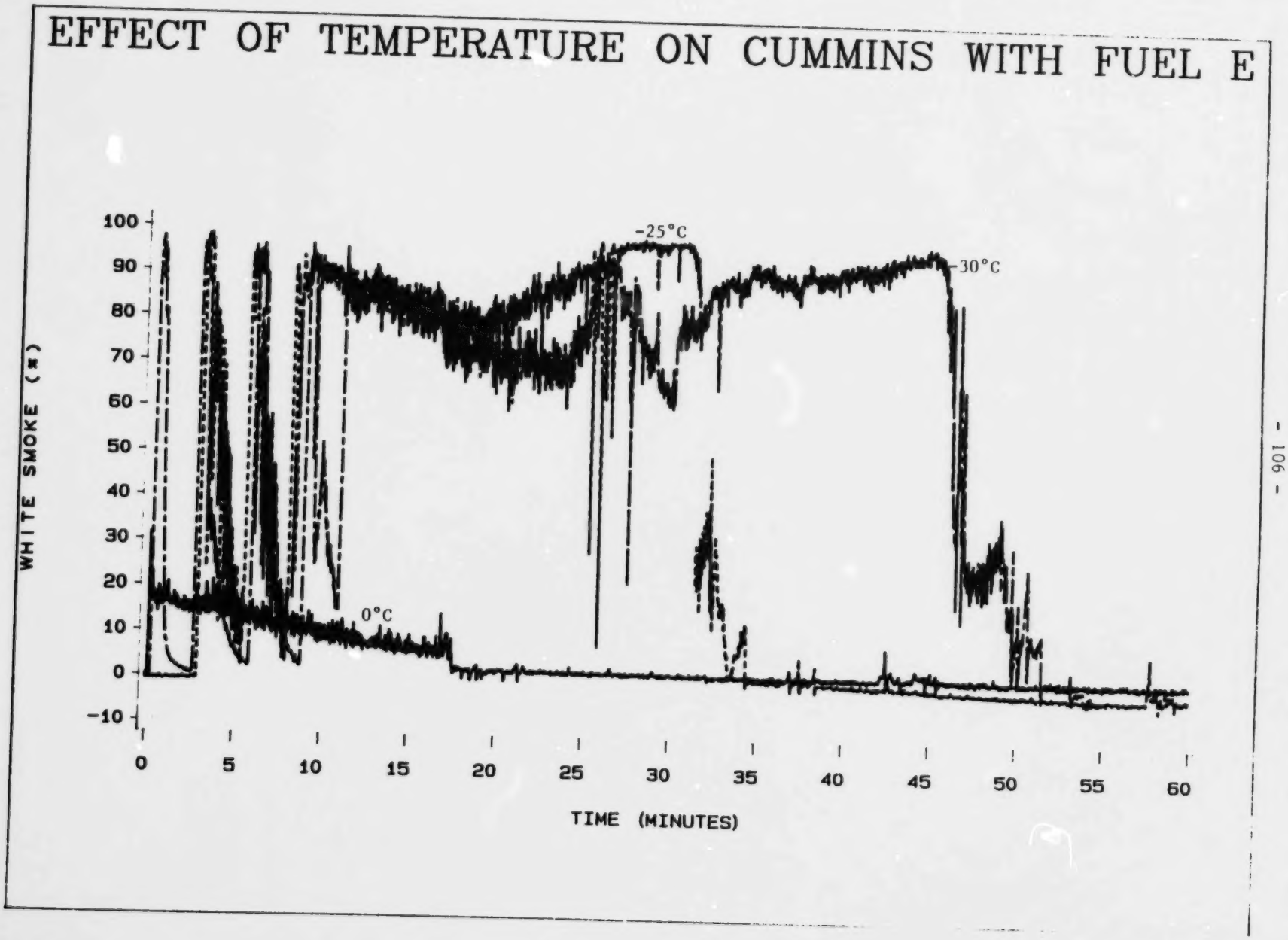

EFFECT OF TEMPERATURE ON CUMMINS WITH FUEL E
WHITE SMOKE (%)
100
90
80
70
60
50
40
30
20
10
0
-10
-25°C
-30°C
0°C
0
5
10
15
20
25
30
35
40
45
50
55
60
TIME (MINUTES)

FIGURE 27

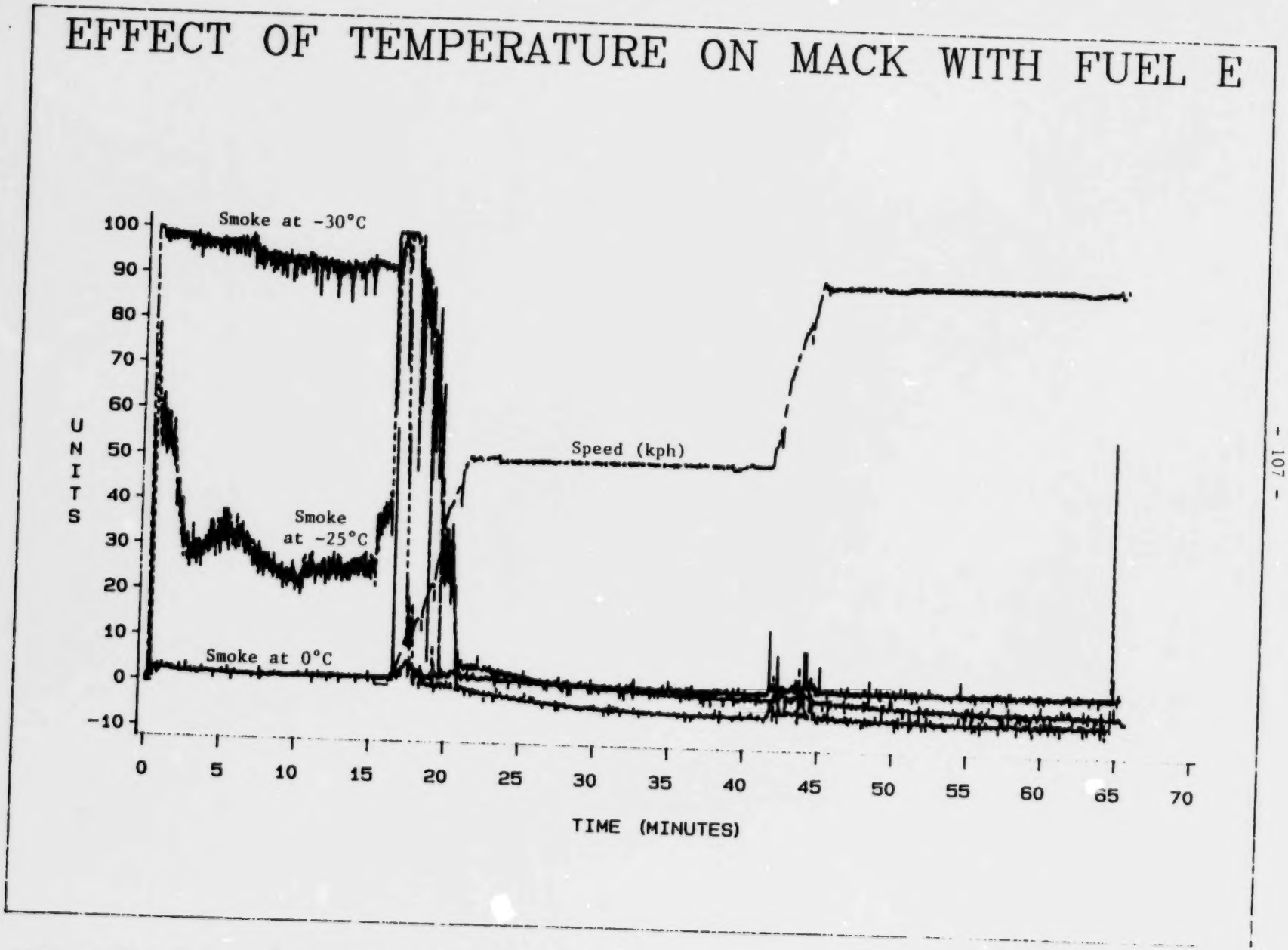

EFFECT OF TEMPERATURE ON MACK WITH FUEL E
Smoke at -30°C
Smoke at -25°C
Smoke at 0°C
Speed (kph)
UNITS
100
90
80
70
60
50
40
30
20
10
0
-10
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
TIME (MINUTES)

FIGURE 28

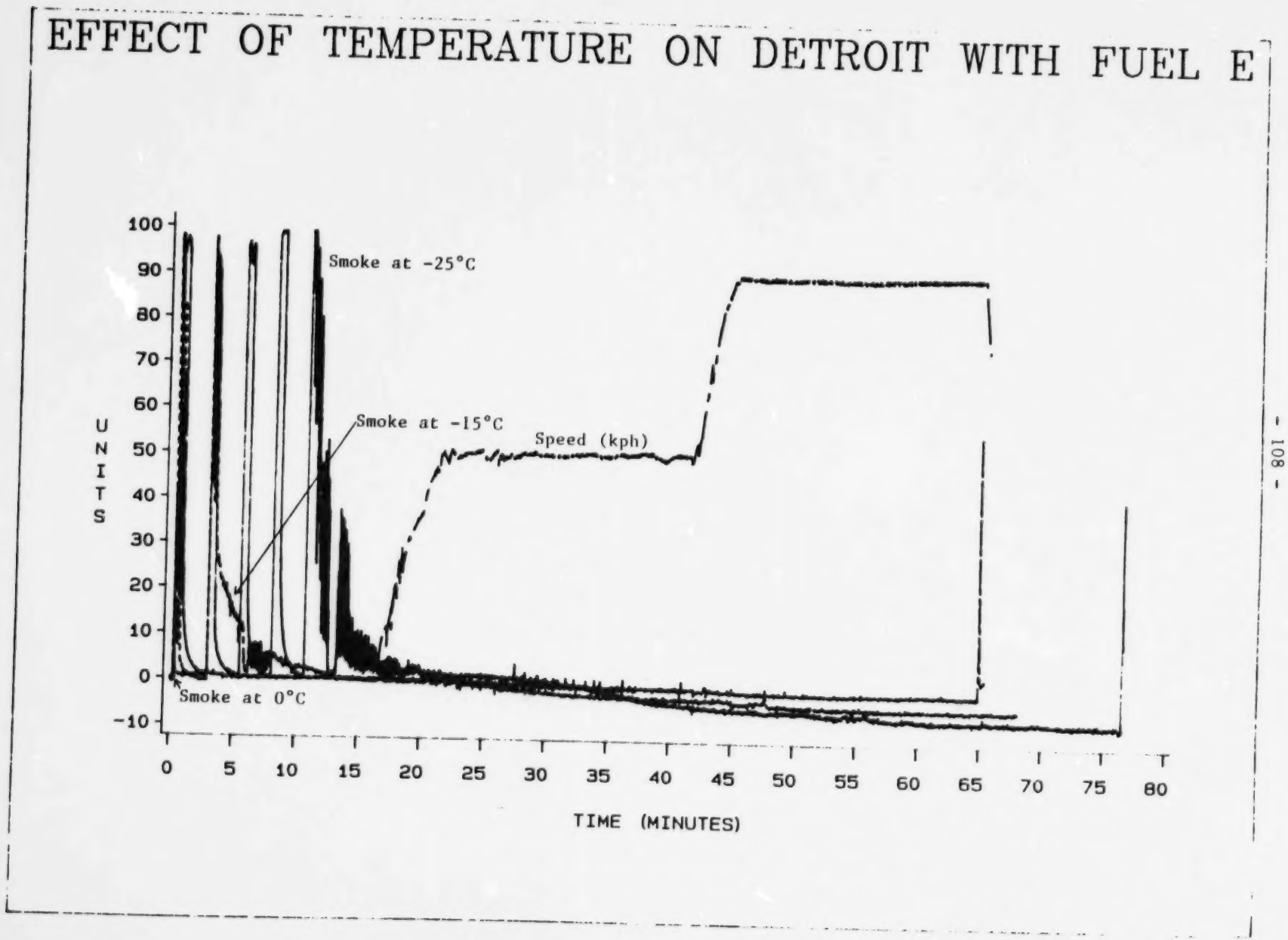

EFFECT OF TEMPERATURE ON DETROIT WITH FUEL E
Smoke at -25°C
Smoke at -15°C
Speed (kph)
Smoke at 0°C
UNITS
100
90
80
70
60
50
40
30
20
10
0
-10
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
TIME (MINUTES)

FIGURE 29

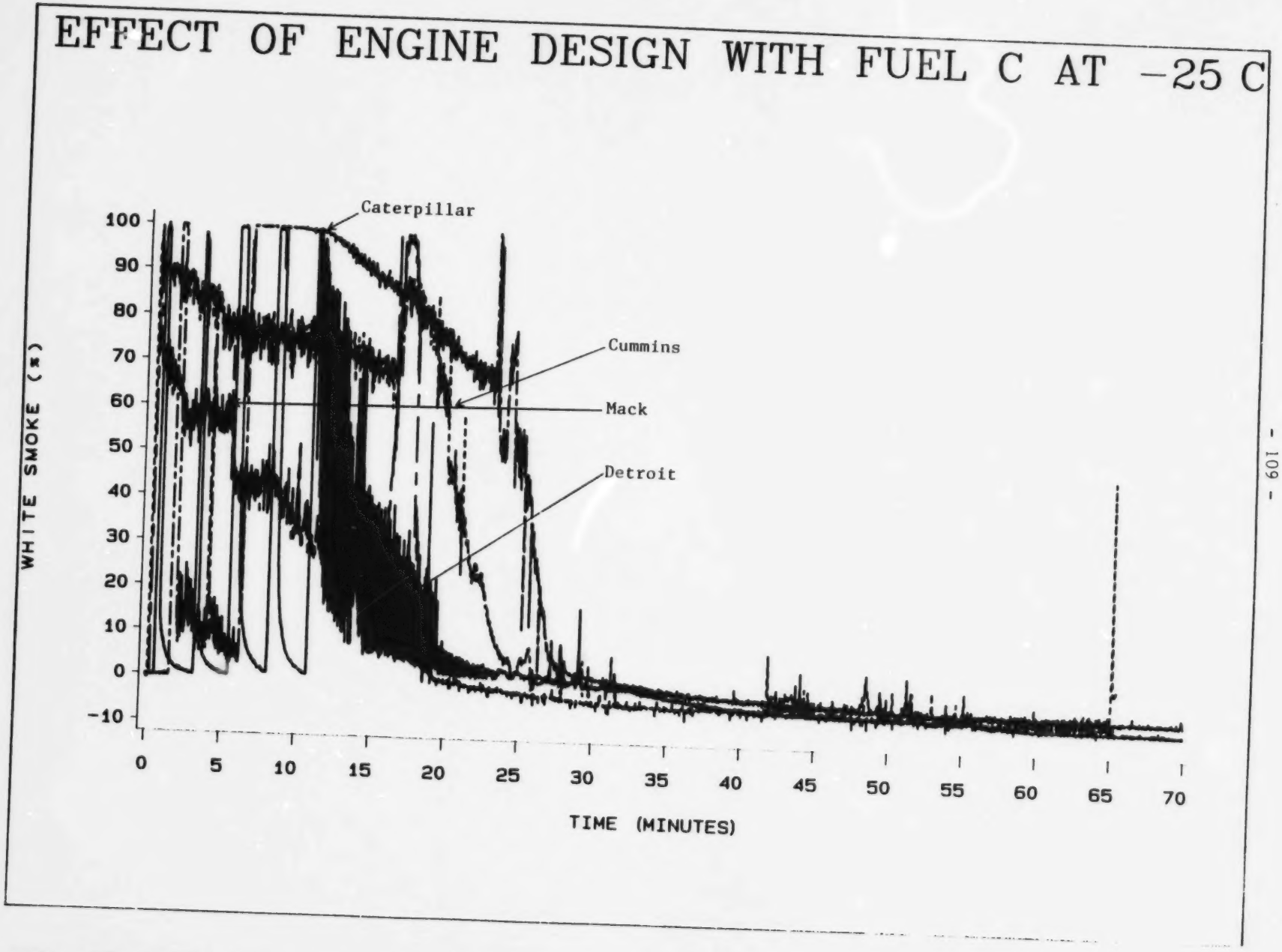

EFFECT OF ENGINE DESIGN WITH FUEL C AT −25 C
WHITE SMOKE (%)
100
90
80
70
60
50
40
30
20
10
0
-10
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
TIME (MINUTES)
Caterpillar
Cummins
Mack
Detroit

FIGURE 30

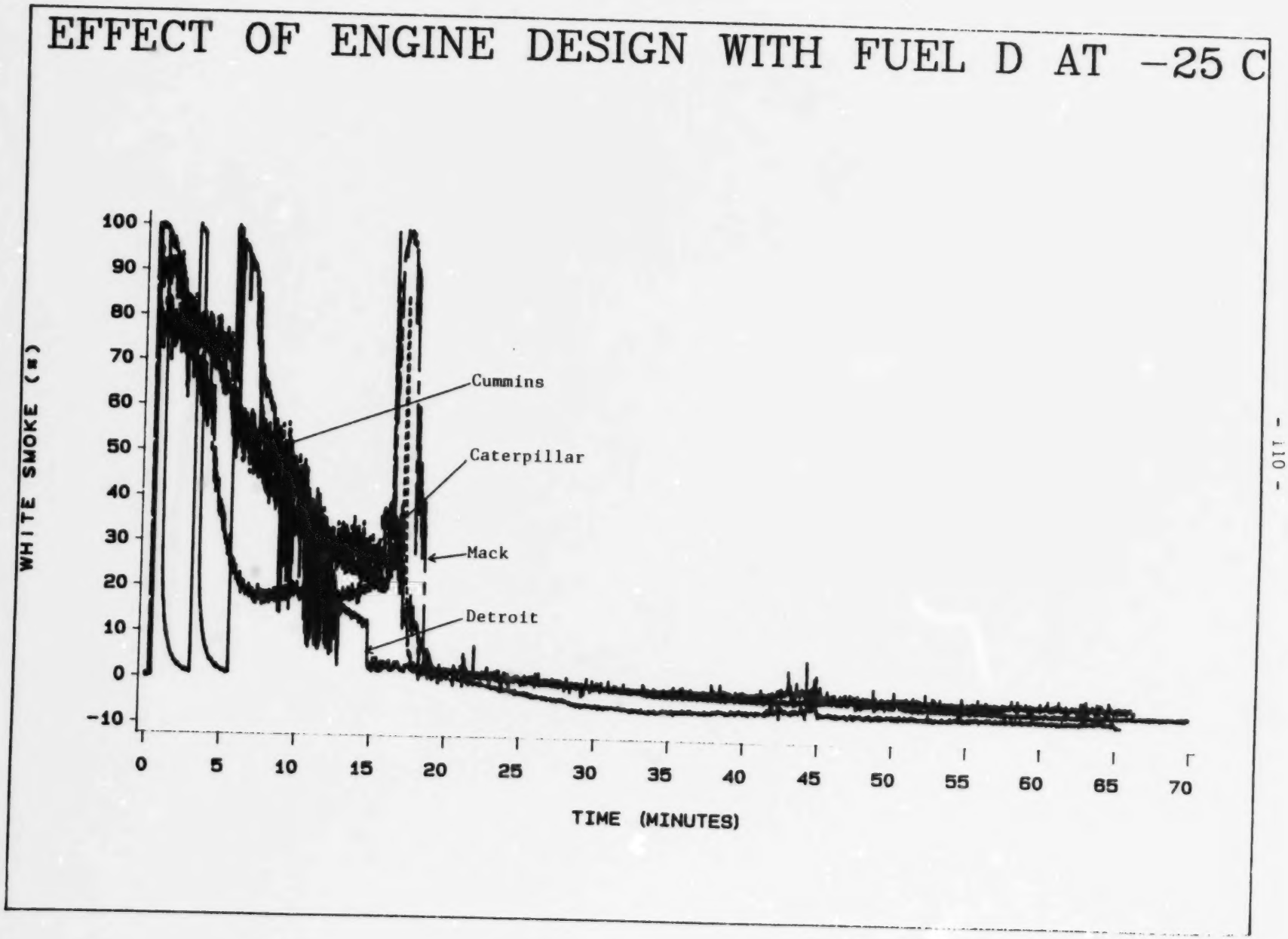

EFFECT OF ENGINE DESIGN WITH FUEL D AT −25 C
WHITE SMOKE (%)
100
90
80
70
60
50
40
30
20
10
0
-10
Cummins
Caterpillar
Mack
Detroit
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
TIME (MINUTES)

FIGURE 31

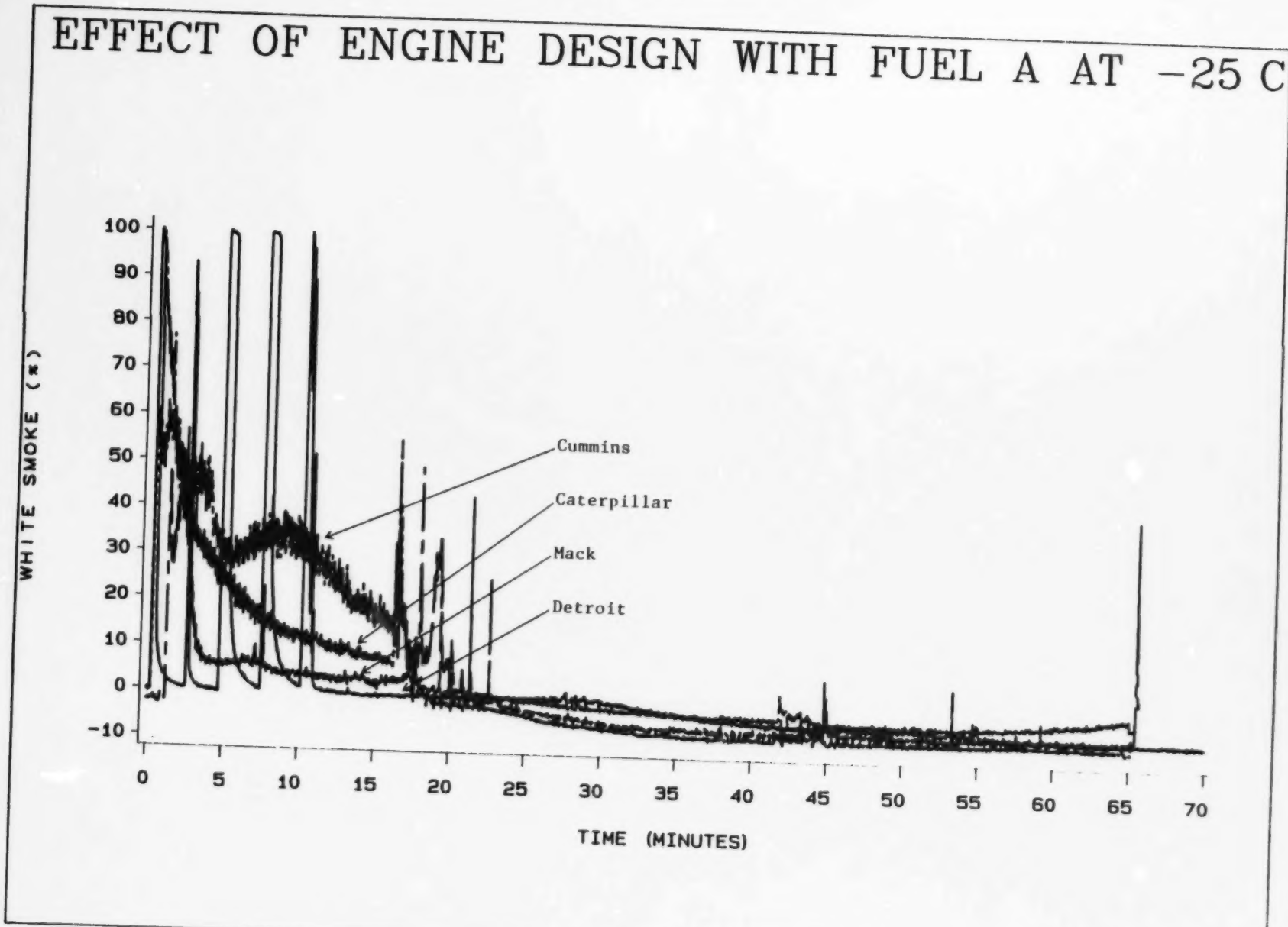

EFFECT OF ENGINE DESIGN WITH FUEL A AT −25 C
WHITE SMOKE (%)
100
90
80
70
60
50
40
30
20
10
0
-10
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
TIME (MINUTES)
Cummins
Caterpillar
Mack
Detroit

FIGURE 32

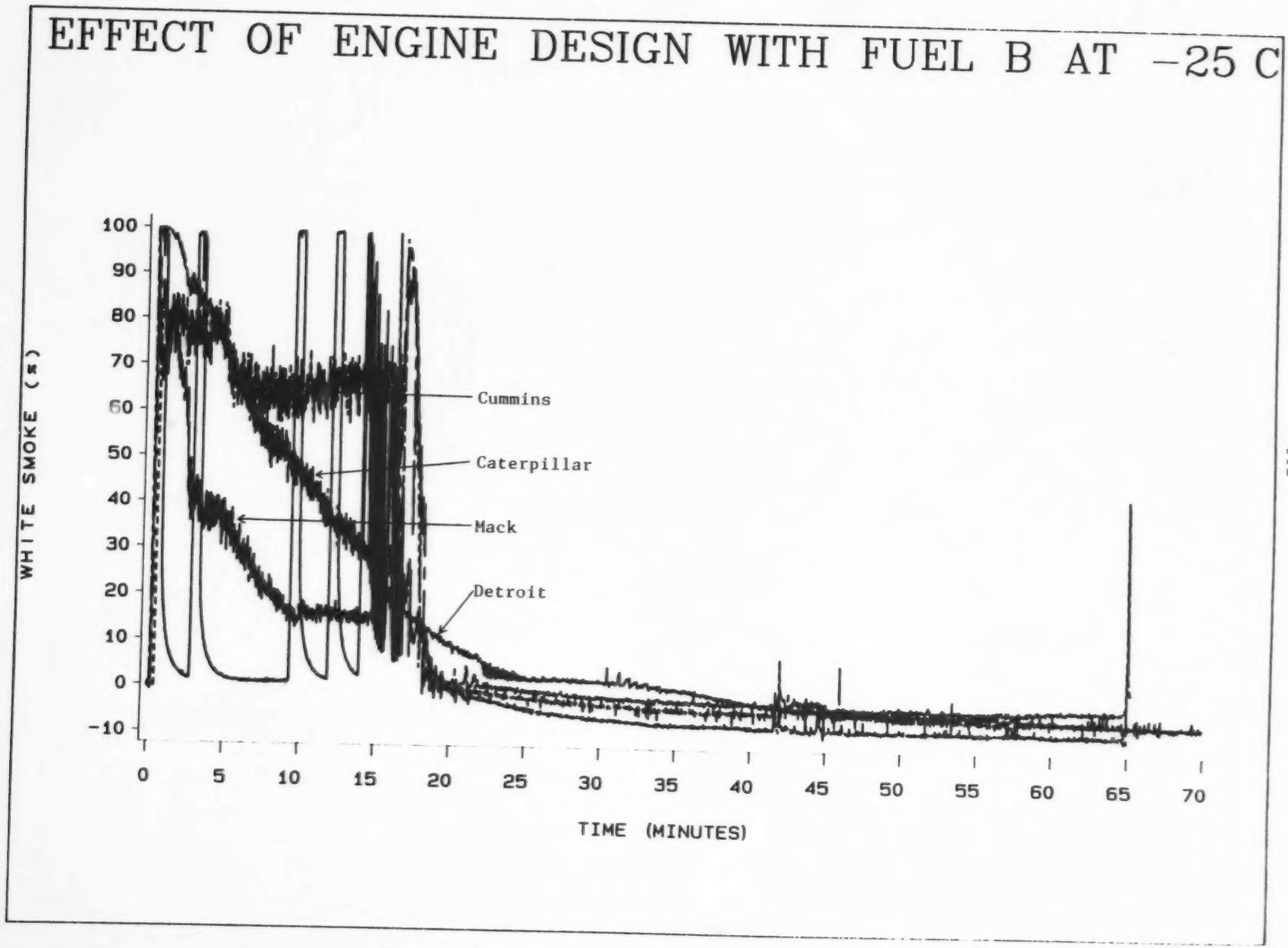

EFFECT OF ENGINE DESIGN WITH FUEL B AT -25 C
WHITE SMOKE (%)
100
90
80
70
60
50
40
30
20
10
0
-10
Cummins
Caterpillar
Mack
Detroit
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
TIME (MINUTES)

FIGURE 33

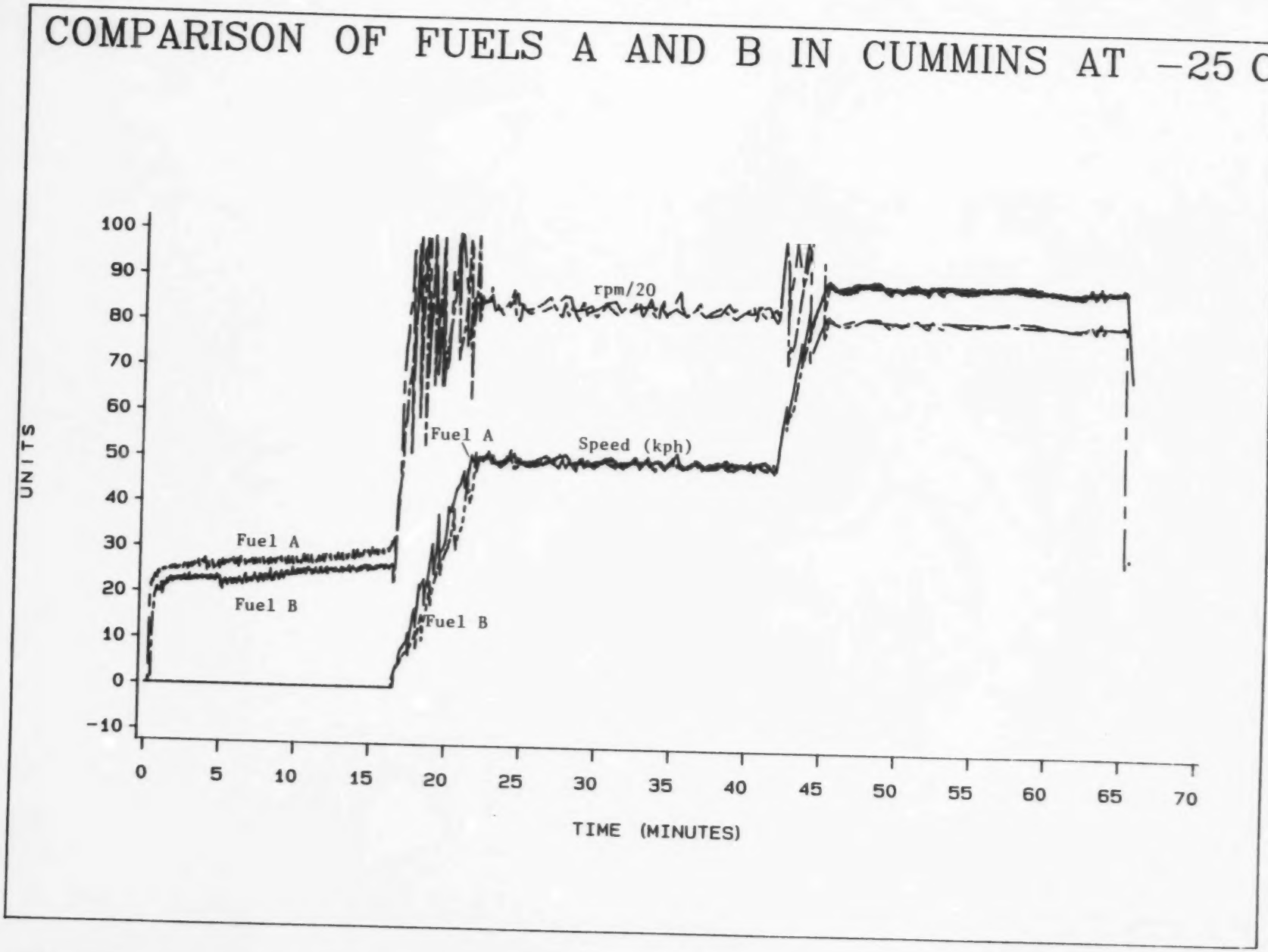

COMPARISON OF FUELS A AND B IN CUMMINS AT −25 C
UNITS
100
90
80
70
60
50
40
30
20
10
0
-10
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
TIME (MINUTES)
rpm/20
Fuel A
Speed (kph)
Fuel A
Fuel B
Fuel B

FIGURE 34

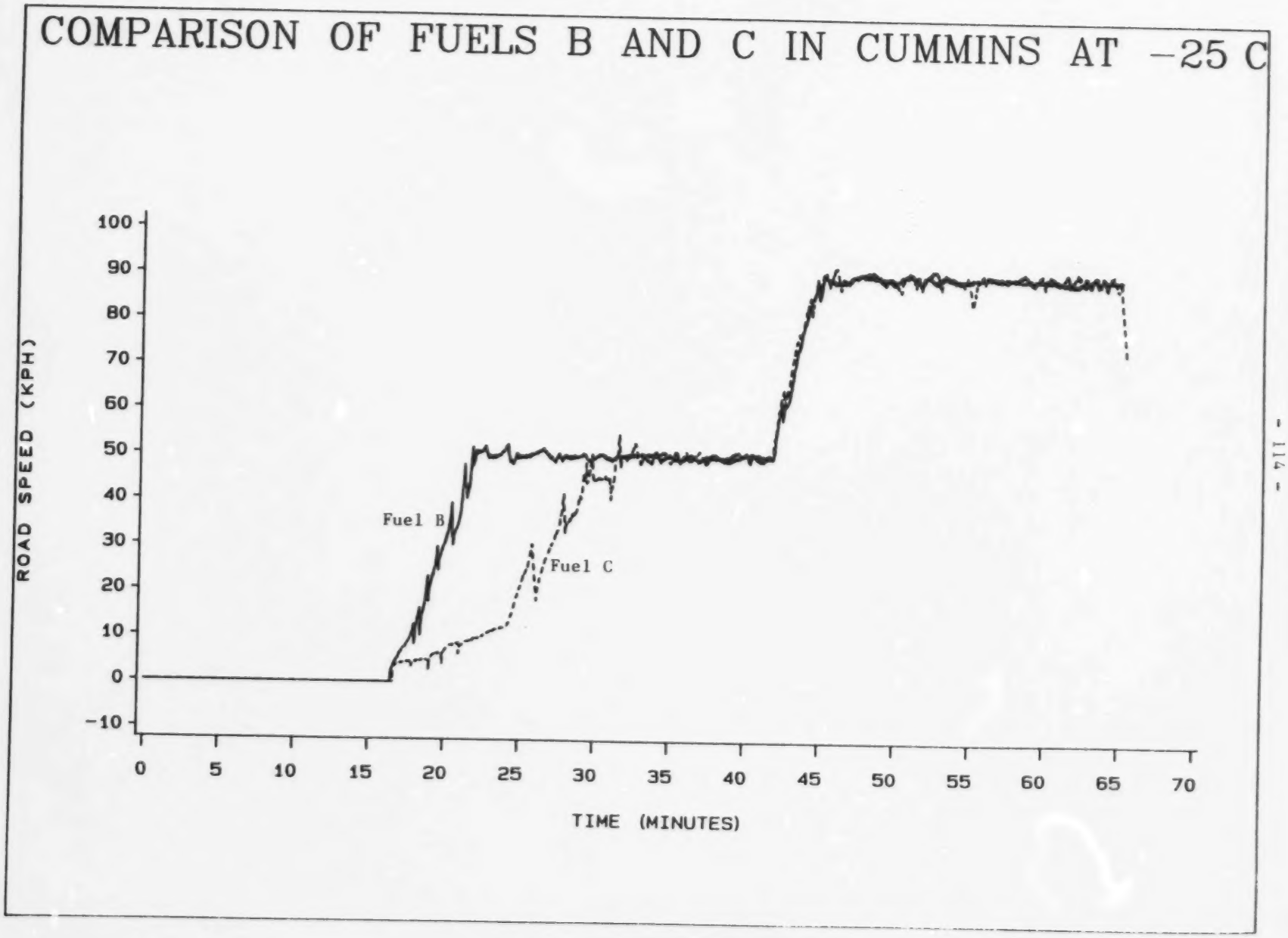

COMPARISON OF FUELS B AND C IN CUMMINS AT -25 C
ROAD SPEED (KPH)
100
90
80
70
60
50
40
30
20
10
0
-10
Fuel B
Fuel C
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
TIME (MINUTES)

FIGURE 35

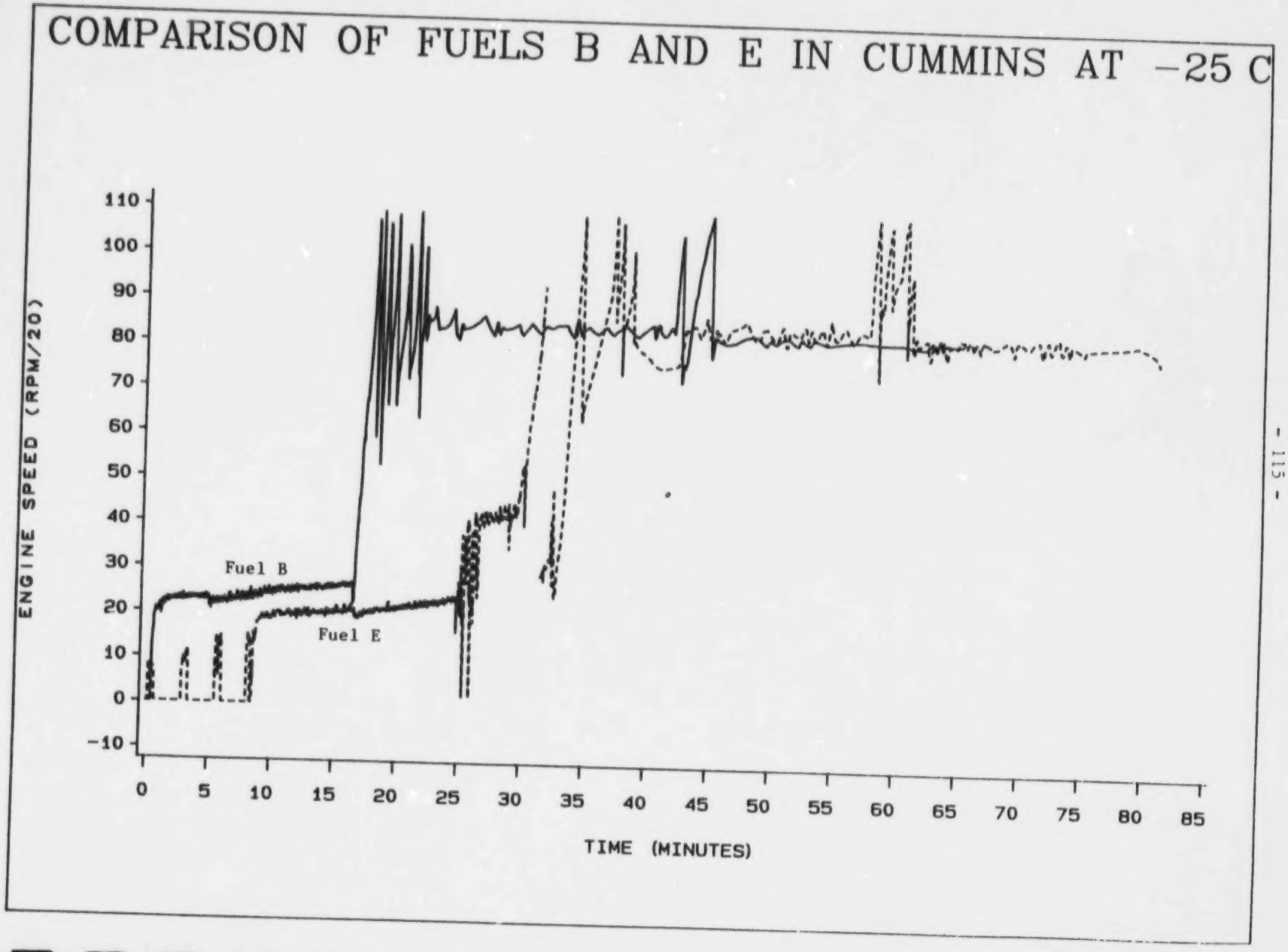
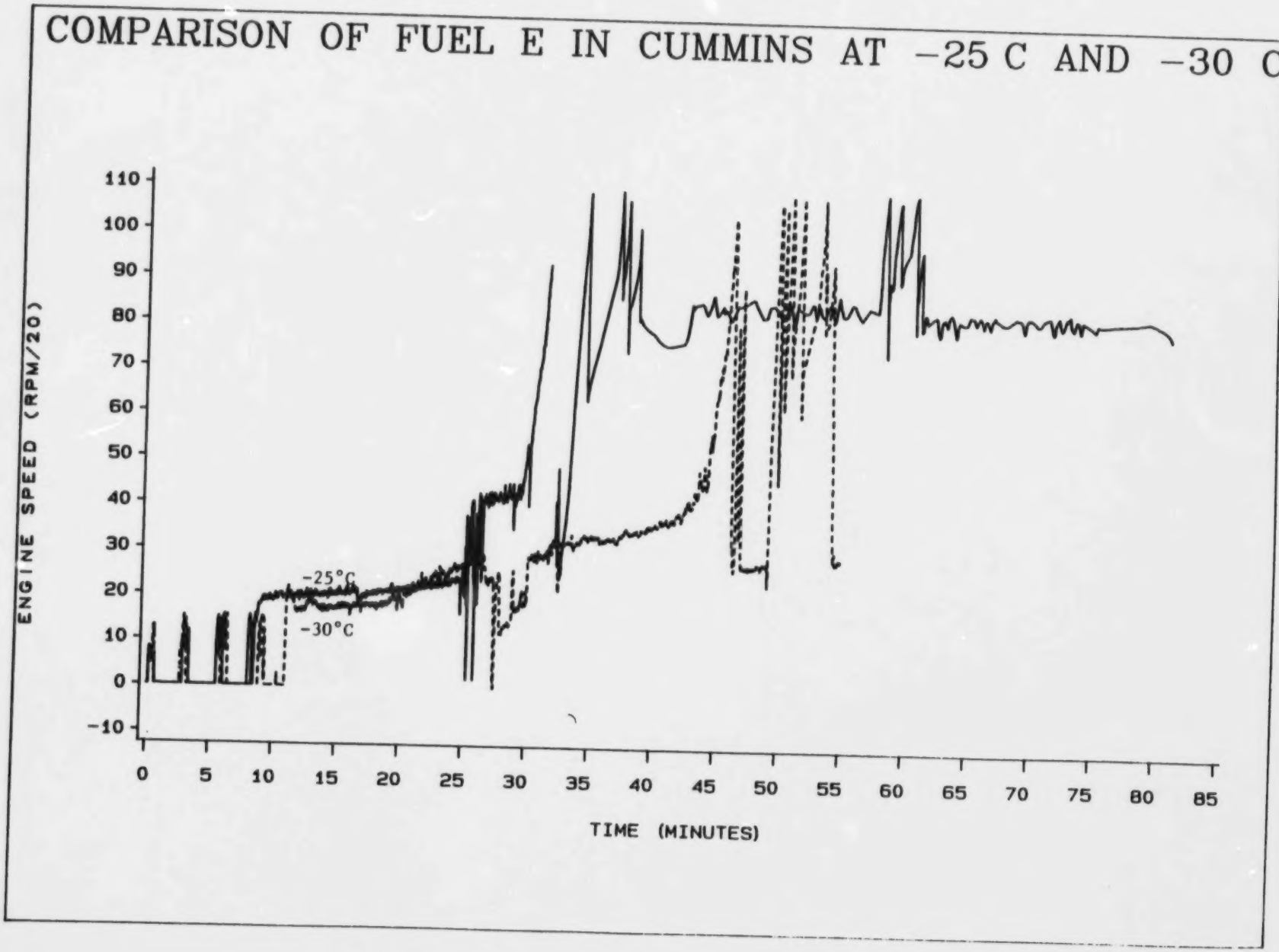

COMPARISON OF FUELS B AND E IN CUMMINS AT -25 C
ENGINE SPEED (RPM/20)
110
100
90
80
70
60
50
40
30
20
10
0
-10
Fuel B
Fuel E
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
85
TIME (MINUTES)

FIGURE 36


COMPARISON OF FUEL E IN CUMMINS AT −25 C AND −30 C
ENGINE SPEED (RPM/20)
110
100
90
80
70
60
50
40
30
20
10
0
−10
−25°C
−30°C
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
85
TIME (MINUTES)